ICWIM7

7th International Conference on Weigh-in-Motion

& PIARC Workshop

Editors : Franziska Schmidt, Bernard Jacob

Foz do Iguaçu, November 7-10, 2016

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PartI: ICWIM7

Preface

The International Conference on Weigh-In-Motion (ICWIM7) is the first of the series organized in Latin America. LabTrans/UFSC (Transportation and Logistic Laboratory of Federal University of Santa Catarina, Brazil) and IFSTTAR (French Institute of Science and Technology of Transport, Planning and Networks) brought a strong support to the International Society for Weigh-In-Motion (ISWIM) to host and organizing a successful conference.

ICWIM has a rich history, with a series of 7 conferences held in 4 continents: Zürich (1995), Lisbon (1998), Orlando (2002), Taipei (2005), Paris (2008), Dallas (2012) and now Foz do Iguaçu (2016). Two of these conferences (2002 and 2012) were combined with NATMEC (North American Travel Monitoring Exhibition and Conference), and one (2008) with HVTT (Heavy Vehicle Transport Technology) conferences.

ICWIM7 is hosting an International Workshop organized by the PIARC (Word Road Association) TC B4 on Freight Transport.

ICWIM has covered WIM technologies, systems and sensors, standards, testing and applications of WIM to traffic monitoring, infrastructure engineering and enforcement. Road freight transport and heavy commercial vehicles carry a significant part of the goods all around the World, and therefore is an essential factor of the economical growth. However, the road transport sector contributes to the GNG emissions and the climate change, to the fossil energy consumption and to the air pollution. Sustainable road freight is a major challenge for the 21st century, both in developed and emerging countries. Beside the vehicle technologies, the driving conditions and vehicle operation, the logistics planning and development, and the vehicle and infrastructure interaction, it is mandatory to ensure a full compliance with weights and dimensions regulations. This becomes even more critical when high capacity vehicles (longer and heavier) are concerned, which is a global trend in several regions of the World.

A strict compliance with the weight limits shall ensure a fair competition in freight transport, a harmonized balance between all modes, the durability and safety of infrastructure with huge cost savings, and an improved road safety. Enforcement of overloads became a major challenge over the two last decades and represents now the main demand for WIM systems. Recent regulations on weights and dimensions are encouraging or requiring more checks and controls of overloads, as the revised European Directive 96/53EC, published in May 2015, which includes a new article on enforcement policy and recommends using WIM systems to collect data and report.

There are also some promising perspectives of using WIM technology for direct enforcement. With the reduction of staff resources, the increasing safety and productivity requirements and the higher traffic volume on highways and motorways, it becomes more and more difficult and less efficient to strop heavy good vehicles for checking on road side. WIM systems are already widely used for many years as an efficient tool for screening and pre-selection of overloaded vehicles. Since a few years, some countries are investigating how improved WIM systems could be used for direct enforcement, the Czech Republic already started that and France launched an ambitious research project on this topic. This requires both accurate WIM systems, with tolerances compatible with the driving law and the accepted tolerances on gross vehicle weights and axle loads, but also a much more reliable data processing and filtering process, to guarantee that 100% of the vehicles measured above the legal thresholds are really overloaded. The type approval by the Legal Metrology is required for this use of WIM systems, which remains a challenge for high speed WIM.

WIM is also now part of a global ITS (Intelligent Transport System) providing useful information for heavy traffic management, heavy good vehicle routing and monitoring, such as in the Intelligent Access Programme (IAP) developed in Australia. WIM systems, and above all B-WIM (bridge WIM) are also more and more integrated in bridge monitoring systems, while all WIM systems are use in pavement monitoring systems, to assess more accurately the in service reliability and capacity of structures, to take appropriate measures to mitigate adverse events such as premature structural ageing or failure, and to increase the safety and durability of road infrastructures.

The conference addresses all these issues and report the latest research and developments since the last conference in 2012, from all around the World. Approximately 150 delegates from 25 countries and all continents are attending ICWIM7, mixing academics, end users, decision makers and WIM vendors. An industrial exhibition is organized jointly with the conference, with 15 companies involved. Beside the scientific and technical and the poster sessions, two panel discussions are addressing timely and important topics, i.e. (i) Data Quality and Applications to ITS, Highway traffic Monitoring and Road Freight Transport, and (ii) WIM for Enforcement and Heavy Vehicle Compliance.

The three main issues of the TC B4 are: (i) National policies for multi-modal freight transport and logistics, (ii) Truck- traffic on highways, and (iii) Good practices on energy-efficient freight transport. The objectives of the joint PIARC workshop on “Multimodal policies and sustainable, safe and energy efficient road freight transport” are to exchange knowledge and experiences, to present and share good practices and to discuss challenges and newest developments regarding freight transport and road network operations. This is a great opportunity to facilitate the exchange and cooperation between members of ISWIM and PIARC.

The conference is supported by International organizations such as PIARC (World Road Association), organizing a TC B4 committee meeting and an International Workshop, the OECD/ITF (International Transport Forum) and the FEHRL (Forum of European Highway Research Laboratories), and by the Federal Department of Transportation Infrastructure of Brazil (DNIT).

We greatly appreciate the support of the major sponsors of the conference: Intercomp, Kistler AG, Q-Free (ex TDC) and Sterela, as well as the regular sponsor (IRD)

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International Society for Weigh-in-Motion (ISWIM)

The International Society for Weigh-In-Motion (ISWIM), an international not for-profit organization based in Switzerland, was born in 2007 and officially launched in 2008, to welcome all with a common interest in WIM. It supports advances in WIM technologies and promotes more widespread use of WIM and its widespread applications.

Organizing WIM conferences and seminars is a major objective. ISWIM successfully held 6 International conferences on Weigh-in-motion (ICWIM1 to 6) since 1995, successively in Zurich, Lisbon, Orlando (Florida), Taipei, Paris and Dallas (Texas). In addition an International Seminar was organized in Florianopolis (Santa Catarina, Brazil) in 2011, with the support of the DNIT (Department of Transport of Brazil) and the Federal University of Santa Catarina).

The TRB subcommittee on WIM (ABJ 035-2) is forming a the North American regional group of ISWIM, the European community of WIM initially formed through the COST323 management committee (1992-98), and the Latin American WIM group are the active regional groups of ISWIM. ISWIM is also active on the Internet through its newly redesigned web site http://www.is-wim.org. This web site offers an
International portal for WIM, with many resources, such as scientific and technical publications, links to WIM web sites, and facilitates exchanges of WIM experiences. The website also hosts the pages of the
affiliated vendors forming the Vendor College. ISWIM has a scientific interest in supporting WIM standardization initiatives such as the recently European standard submitted to the vote of the EU members states by the CEN (European Committee for Standardization). ISWIM is promoting common tests and assessment of WIM systems and WIM applications in exposing end-users to the myriad of uses.

ISWIM consists of individual and corporate members. The Vendors College comprises 16 commercial enterprises, mainly WIM system manufacturers and vendors. There is a Board of up to 15 members which is elected by the General Assembly of all members. There is no membership fee for individuals. There is
a membership fee for companies and organizations.

You are invited to join ISWIM and become an active member of the ISWIM community by signing up on the ISWIM web site: **http://www.is-wim.org.**

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The World Road Association is a non-profit association established more than 100 years ago to promote international cooperation on issues pertaining to roads and road transportation. It consists of a wide range of members from every part of the globe. The core members are road agencies representing over 120 countries. The Association mobilizes the expertise its members to share and develop information for the benefit of the global transportation community, a mission that is grounded in the needs of member countries and supportive of larger trends in global society.

It fulfils this mission through operations guided by a 4-year Strategic Plan. For this 2016-2019 cycle, there are five strategic themes:

A: Management and Finance
B: Access and Mobility
C: Safety
D: Infrastructure
E: Climate Change and Environment

These themes represent a continuation of work that remains at the core of road agencies' interest as well as the emergence of concerns about how to address the need of road infrastructure to withstand conditions imposed by short-lived extreme weather events and changes in long-term weather patterns. Within these themes are a total of 18 Technical Committees and 4 Task Forces. In addition to the five strategic themes, the Committee on Terminology will continue its transversal activity.

More information: **www.piarc.org**

TC B4 Freight

The Technical Committee B4 Freight is part of the strategic theme B: Access and mobility. The goal of this Strategic Theme is to encourage the improvement of access and mobility provided to the traveling public and industry through efficient road network operation and integration with other transport modes. Effective and efficient freight transport is an essential contributor to every economy. Within the cycle 2016-19 the following three topics are addressed in TC B4:

- National policies for multi-modal freight transport and logistics: Within this topic countries' national policies for freight transport and logistics, including best practices in evidence-based freight transport policy-making and evaluation for initiatives are investigated and documented.
- Truck- traffic on highways: Within this topic best practices are identified and evaluated regarding access management, traffic regulations, monitoring, compliance, enforcement
- Energy-efficient road freight transport: Within this topic good practices on energy-efficient freight transport (technical, operational, logistics, regulatory, and infrastructure) are identified and evaluated.

Martin RUESCH
TC B4 chair
RAPP, Switzerland

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Panel Discussions

Panel Discussion 1

Data Quality and Applications to ITS, Highway traffic Monitoring and Road Freight Transport

Chairs: Chris Koniditsiotis (TCA, Australia) & Martin Ruesch (RAPP, Switzerland)

Panel Discussion 2

WIM for Enforcement and Heavy Vehicle Compliance

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PartI: ICWIM7

Session 1 : WIM Technologies

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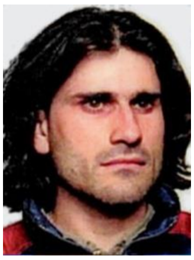
DEVELOPMENT AND TECHNOLOGY TRANSFER OF A WEIGH IN MOTION SYSTEM IN ARGENTINA

J. JORGE **I. MORETTI** **J. AMADO** **D. PUNTILLO** **C. CANIGLIA**

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Abstract

With a transportation system centered on the roads, and a very deficient railway infrastructure, it is increasingly important to do proper planning and design of Highways of our country and more specifically of our province. In this context, the Department of Roads of the Province of Córdoba and the National Institute of Industrial Technology (INTI) initiated a joint project for the development and construction of an inexpensive, adaptable to the conditions of the region, and with local support prototype of a high-speed weigh in motion system that it could be produced in our country. This paper presents the process of design, implementation, calibration, testing and technology transfer of a WIM system for statistical purpose, developed entirely in an institution of the national state and transferred to the productive sector. The current status of WIM in Argentina and future prospects are also mentioned.

Keywords: Weigh In Motion, high-speed WIM, WIM development kit.

Resumen

El sistema de transporte argentino está centrado en las carreteras por lo que cada vez es más fuerte la necesidad de realizar una correcta planificación y diseño de las rutas de nuestro país, y puntualmente de nuestra provincia. En este contexto, la Dirección de Vialidad de la Provincia de Córdoba y el Instituto Nacional de Tecnología Industrial (INTI) inician un proyecto conjunto para el desarrollo y construcción de un sistema de pesaje dinámico de bajo costo, adaptable a las condiciones de la región, con soporte local, y que pueda ser producido en nuestro país. En esta publicación se describe el proceso de diseño, desarrollo, implementación, verificación, calibración, pruebas, y transferencia tecnológica de este sistema, completamente desarrollado en una institución del estado y transferido al sector productivo. Se muestra el estado actual del área en Argentina y se mencionan las perspectivas futuras.

Palabras Claves: Pesaje en movimiento, WIM de alta velocidad, prototipo WIM.

1. Introduction

Argentinian transportation system is centered on the roads; we have a very deficient railway infrastructure. Road transport in Argentina has a decisive weight in the total cargo movement (which includes exports, imports and domestic cargo). Currently more than 90% of the total load is delivered by road transport (Barbero, J. 2013). In contrast, the railway carries only a little more than 5% of the loads and water transport 1.5%, Figure 1 depicts this distribution and exports distribution.

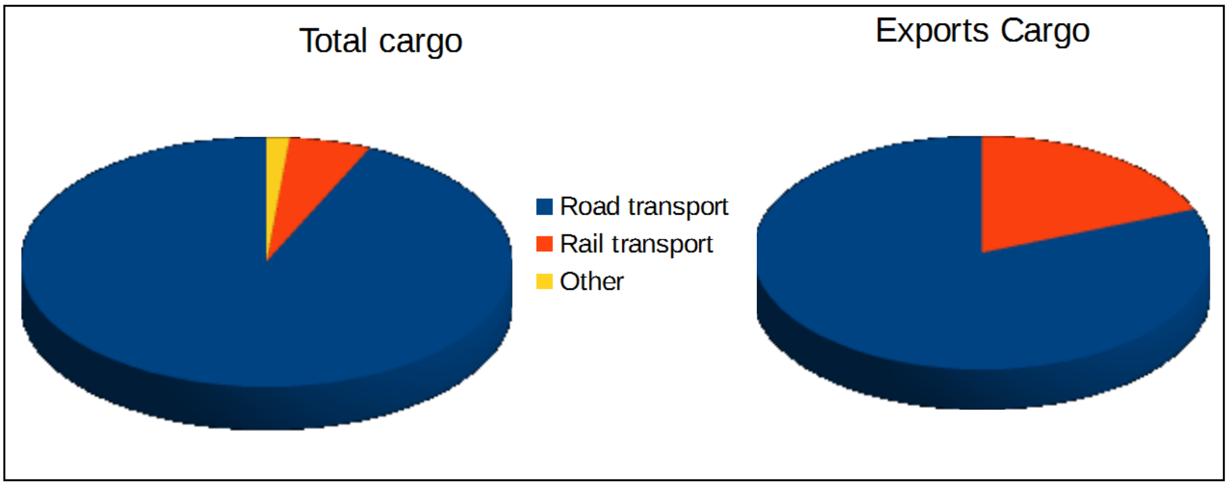


Figure 1 – Transport type participation for total cargo and export only cargo.

Argentinian export cargo volume is expected to increase by about 25% in the next decade. It is increasingly important to do proper planning and design of Highways of our country and more specifically of our province. To accomplish this objective it is essential to have characterization of current traffic volumes on the road network. In addition, it is also necessary to avoid the circulation of overloaded vehicles. Current controls are not being effective because Argentina only has static weighing stations and a very small number of operators. There are some groups of operators with portable static scales but permanent stations are essential. It is very important to have a more effective load control and new road enforcement systems to avoid premature deterioration of the highways.

This scenario serves as an indispensable starting point in the implementation and design of traffic monitoring and control plan that includes WIM systems as data providers. In this context, in 2009 the Department of Roads of the Province of Córdoba and the National Institute of Industrial Technology initiated a joint project for the development and construction of an inexpensive, adaptable to the conditions the region, and with local support prototype of a high-speed weigh in motion system that it could be produced in our country.

The paper presents the process of design, development, implementation, calibration, validation, and technology transfer of a WIM system for statistical purpose, developed entirely in an institution of the national state and transferred to the productive sector. The most important aspects of the development process, verification and calibration of the system, methodologies, current applications, its scope and limitations are also summarized.

Given the incipient progress in this area in our country, it has also begun to outline a draft of metrological and technical requirements as well as the methods of certification for high-speed weighing equipment that allows direct enforcement, which currently cannot be performed due to the absence of corresponding legislation. The current status of WIM in Argentina and future prospects are also mentioned.

2. Development Process

A prototype driven development (PDD) approach was adopted. Each prototype was used to test different components of the system. The reason why PDD was adopted by this project was that specific knowledge of the whole system and specific requirements were not available at the beginning of the project. By continuously creating, improving, and interacting with prototypes devices can be launched faster, with higher quality and with a stronger focus on the customer's needs.

In this context, a prototype is a good tool to learn form a technology. Each prototype was developed using a reduced version of the V model (Turner, R. 2013). The main advantage of V model is that test plan and test design is conducted as soon as the design process is done. Then once an artifact has been implemented, the testing stage can take place.

Initial planning for the first prototype took lot of time. INTI development group members had already had an experience with WIM sensors back in 1998, but by the time the development started the technology had evolved a lot. After the initial planning a sketch of the initial requirements and an architecture design was made. With that in mind each group started a detailed design and implementation of the components. Meanwhile in parallel the team started the building of the WIM site and performed the sensors installation. Once the sensors where in place, the team proceeded with the capture of real signals to aid the development process in the lab.

The first prototype "P0" was just a charge amplifier, and a small system capable of integrate the signal and measure the time between axles. With this device integration capabilities and weight calculation algorithms were designed. By that time the weight calculation was done after the each field measurements back in the lab. The next prototype "P1" added a control module that gives it full weigh-in-motion capabilities. This new device was able to measure speed, weight and classify the vehicles. This new capabilities where tested and the need of axle inconsistency detection arises. The last prototype included a printed circuit board (PCB) redesign (noise reduction), system calibration and performance evaluations, and major software upgrades (Figure 2).

3. The final Prototype

The system is designed to work in a distributed fashion. This means several data acquisition equipment are spread in different roads and transmit collected data to a predefined statistical data center (Figure 2). This allows remote monitoring of traffic flow of different places. Data acquisition devices can also operate autonomously, as a measurement station, and data can be extracted locally.

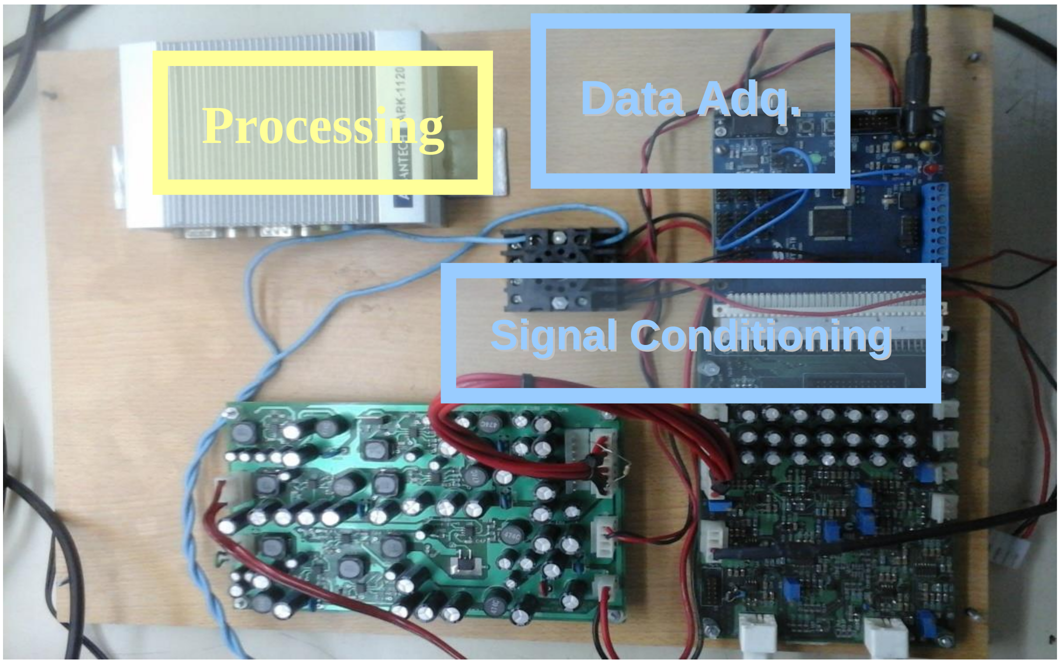


Figure 2 – Photograph of the final PCBs

3.1 Block Diagram

This block diagram (Figure 3) depicts the main sections of the final prototype and its interactions. Vehicles interact with sensors, Signal conditioning block transmits voltage signal to the acquisition block. This last block preprocesses the signal and re transmits the most important information to the processing unit. Once the weight, speed and type of vehicle are calculated, all this information is packed into a register that is sent to a concentrator.

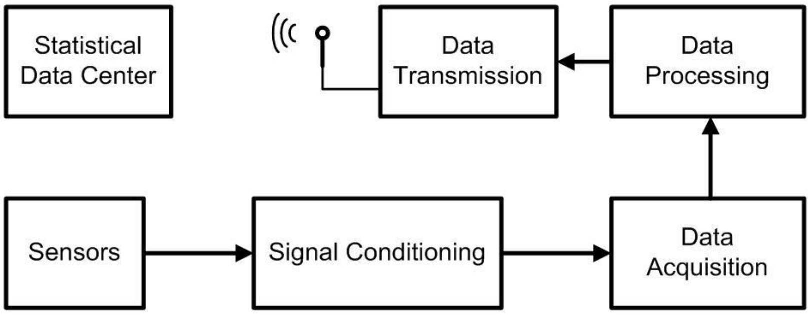


Figure 3 – Simplified block diagram

3.1.1 Sensors

This prototype has five sensors, two inductive loops, two 6' (1.82m) Class I (WIM) RoadTrax BL Piezo Sensors and one temperature sensor.

3.1.2 Signal Conditioning

The idea of this block is to transform charge signal into voltage, extract some indicators and reduce the dynamic range of the signals at the input of the ADC.

3.1.3 Data Acquisition

This block contains a 100 MIPS 8 bit microcontroller that converts the analog data into digital and preprocesses the signal. It acquires raw data and transmits this data to the processing block.

3.1.4 Data Processing

This block is based on an x86 32bit system, capable of receiving real time raw data and post process this data in order to produce relevant information such as weight, speed, classification etc. This block also performs surveillance over the performance of the whole system.

3.1.5 Data Transmission

Data transmission is performed over a network of computers and it is independent of the hardware, it can be throw an Ethernet connection, a GPRS modem or a WIFI connection depending on the available infrastructure.

3.1.6 Statistical Data Center

This is a software application that concentrates information from different devices and processes it in order to give statistical information of each device. The software was programmed to meet the needs of local road authorities

3.2 Piezo electric sensor characterization

At the beginning of development only nominal transfer function of the sensor (pC / Nt) and the maximum error along it where known. In order to acquire a detailed knowledge of the sensor's response, and especially its variation with respect to temperature, extensive measurements were performed on the sensors installed on the road in the experimental site. Measurements were performed at different speeds, different weights and different temperatures; this helped us to characterize the variation of the sensor gain against these parameters. Then algorithms that compensate for these variations were developed. Obtained results are similar to that of Kwon (2016).

3.3 Test site description

Field measurements where done in an experimental test site. This site was chosen in order to help the development and the serve as a permanent WIM site and real time traffic monitoring station. The site was constructed with the aid of the national direction of the Department of Roads of the Province of Córdoba. The chosen place corresponds to road C45, at 40km from Cordoba city (Figure 4). This road is often used for legume and cereal transport from the farms to the nearest silo. This road was also chosen because it has some conditions similar to most Argentinean roads; it’s made of asphalt and has some deformations.
The site corresponds with criteria for the choice of WIM sites according to the literature and the European WIM specification (1999), Chapter 5, and was evaluated as Acceptable.
All the electronic was located in a bunker at approximately 15 m from the road, to achieve a distance that is safe enough to avoid accidents and give more comfortable measurement conditions and not so far to use shorter cables.

Figure 4 – sensors and test truck

4. Prototype Validation

The system validation included a complex set of tests, unit tests integration tests and system tests. This section will summarize some of the most important tests and its results

4.1 Weigh validation

The weighing process includes the measurement of vehicle speed and the sensor signal integral calculation. Each block was first individually validated, and then integrated. The system speed measurements were first validated in laboratory. Using a digitalized signal obtained from a real vehicle. The signals were replicated using an arbitrary signal generator. The speed measurement error was within the 0.2% for all measurements. Some integration tests where done in software. Some integration tests and functional tests were done in order to check that the results obtained in the unit tests against simulated values reach the data base and the frontend. Then the system was validated in field against INTI national speed reference device. All measurements errors where less than 1.5% Integral calculations were also validated separately using a laboratory signal generation pattern. This pattern is also validated against international signal generator patterns. Integral measurements revealed that errors was allays less than 0.8%. The temperature sensor was also calibrated against INTI temperature patterns.

4.1.1 Calibration

The calibration method implemented was the “Pre-Weighed Calibration Lorries” according with COST 323. The main task was to estimates the variation of the thermal sensibility of the two piezo electric sensors. The estimation function was a lineal approximation according to passing some test pre-weighed vehicles over the WIM system. This test plan calibration consisted in 30 events of different vehicles, weights and speed levels. The class of vehicle was type 2, the weights were between 8t and 16t and the speed levels were between 30km/h to 90km/h. This process consisted of three consecutive days of measurements over six months.

According to Principles of Weigh-in-Motion using Piezoelectric Axle Sensors (Brown, R. H. 2001), the weight of the vehicle is calculated by integration of the axle-crossing waveform. The integral *I* must then be scaled (multiplied) by the vehicle speed *V*. This quantity (time integral of charge or voltage, multiplied by speed) is then proportional to the total load applied during the axle crossing. Then, the weight *P* is calculated as Equation 1:

$$P = I \,.\, V .\, k \qquad (1)$$

where *k* is the sensibility of the sensor and depends on the temperature. The calibration process goal is to estimate this function. This approximation result for the first sensor is given in Figure 5.

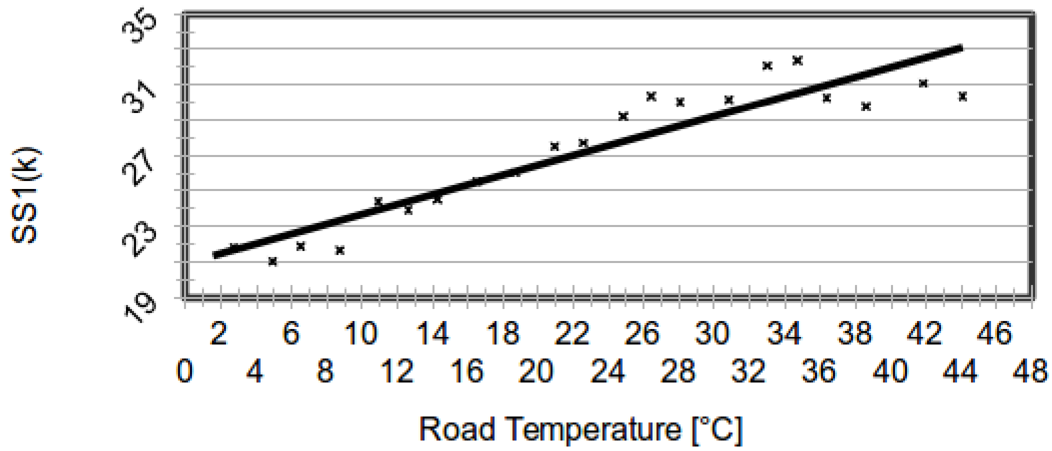


Figure 5 – Thermal Sensibility estimation of sensor 1

4.1.2 Accuracy verification

According to the European WIM specification (COST 323, 1998) the site was evaluated as “III Acceptable”. The site was chosen because it represents the most common route condition in Argentina. For the calibration of the prototype we used Pre-Weighed Calibration Lorries. According to the test plan the environmental repeatability and reproducibility was ***(II) limited environmental reproducibility*** and ***(R2) extended repeatability conditions***. The test for the accuracy verification was at different days, vehicles and weights. In total there were 196 independent events. The results were measured with 5 (five) accurately weighed calibration vehicles, possessing two axles with a gross and axles weight distributed according to Table 1. The vehicles speed varied between 29 and 86 km/h during the measurements. The vehicles were ford cargo 1722, the first (front) axle has rigid axle suspension and second (rear) axle has full floating suspension.

Due to budget restrictions the test site only had two half lane sensors installed consecutively. The system calculates the right wheel weight; the calculated weight is the average of the estimation of both sensors. Dynamic wheel weight calculation error was within 25% for the 95% of the measures, so the prototype cloud is classified as Type I in accordance with ASTM 1318 2009.

The axle weight information was estimated by multiplying the weight of the wheel by two in order to obtain a COST 323 classification. This is merely illustrative because sensor configuration does not allow obtaining a full axle dynamic weigh.

Table 1 – Static loads/weights Ws (kg) calculated in concordance to COST323 procedures

Vehicle	GW	A1	A2
A	8000	4041	3959
B	12240	5039	7201
C	13090	4391	8699
D	15640	4858	10782
E	16240	5059	11181

Table 2 describes some event and the relative error of the measurements.

Table 2 – Some events and its relative error

Nº	T(ºC)	V(km-h)	Type	WD(kg)			WS(kg)			Relative errors(%)		
				GW	A1	A2	GW	A1	A2	GW	A1	A2
1	14,3	40	2	8067	4095	3972	8000	4041	3959	0,84	1,34	0,33
35	8,7	36	2	12283	5086	7196	12240	5039	7201	0,35	0,93	-0,07
77	10,4	41	2	13144	4339	8805	13090	4391	8699	0,41	-1,18	1,22
113	10,9	49	2	15708	4924	10784	15640	4858	10782	0,43	1,36	0,02
162	16,5	58	2	16444	4946	11498	16240	5059	11181	1,26	-2,23	2,84

After that we calculated the mean and standard deviation of relative error of GW and SA the results are described in Table 3.

Table 3 - Relative errors (%) statistics

	GW	SAL
number	196	392
mean	0,64	1,35
st.dev	10,88	13,67

Table 4 summarizes experiments with the vehicles mentioned in Table 1 in the chosen site. The COST 323 European WIM specification accuracy calculated result is E(30).

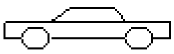
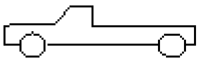
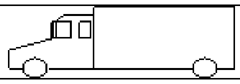
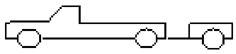
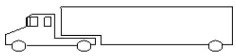
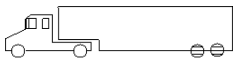
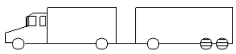
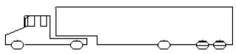
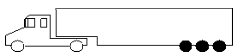
Table 4 – Accuracy calculated results

Conditions (1)	Test plan		Env^t		Initial verification (Yes=1, No=0):					0
	R2		II							
SYSTEM	Number	Identified	Mean	Std deviat	π_o	Class	δ	δ_{min}	δ_c	π
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)	(%)
gross weight	196	100,0	0,64	10,88	96,5	D(25)	25	24,7	24,7	96,7
single axle	392	100,0	1,35	13,67	96,8	E(30)	36	31,0	26,0	98,8

4.2 Classification algorithm and validation

The classification is performed according to the requirements of the National Roads Authority as published in Dirección Nacional de Vialidad (2003), which is based on the separation of the vehicles axles. The classification algorithm was performed by a key-value structure, where vehicles are grouped by type. Each element of the structure contains a list of all vehicles with the same number of axles, whenever it presents a new vehicle it is only necessary compare it against all vehicles having the same number of axes. Besides, it was implemented an automatic sort system that permits to locate the last vehicles identified at the beginning of the list. This classification algorithm was tested in the WIM site and the results are displayed in Table 5.

Table 5 – Classification results

Vehicle type	Outline	Categ. No.	No. of axles	No. of vehicles	No. of classified vehicles	Percentage (%)
Car		2	2	30	28	93,33
Pickup truck		3	2	9	9	100
Truck 11		6	2	34	34	100
Pickup + trailer		3	3	4	2	50
Semi truck 111		10	3	1	1	100
Semi truck 112		11	4	7	7	100
Truck 11 12		9	5	15	14	93,33
Semi 11 (1) 2		12	5	3	3	100
Semi 113		12	5	2	2	100

5. Technology transfer

The developed technology is being transferred to national enterprises for production stages. The main idea is that these enterprises take the development and could make improvements and evolutions of the system to get new commercial products. The transfer process includes training about system development, operation, calibration, use and regulations. And it also provides technical assistance for installation of the measuring station and start up the system.

6. WIM in Argentina

The use of WIM system in Argentina is very poor, there is only a few sites in the whole country, but the need of monitoring the traffic weight is more and more important. In general, the organisms that manage the roads don't have automatic systems to monitor their state. Even the current legislation does not allow overload punishment with dynamic weighing systems. So, the control of load traffic is made using expensive and inefficient static weighing systems. The main important objectives of this project were develop a more inexpensive system that could be produced by national industry, and to produce knowledge in the area of weigh-in-motion of vehicles.

7. Conclusion

A prototype of high-speed weigh-in-motion system has been developed, according to the conditions of the road network in this country. The system is adaptable, flexible, versatile and inexpensive. It has been proven correct operation of the equipment and characterized his error under various conditions of use. Several experiments have been performed, both by simulation and field measurement, verifying the accuracy of the prototype and its high degree of reliability. The next step is to bring the system to a commercial product, working with several companies. The main idea is that Argentinian enterprises be able to evolve this technology and produce commercial devices. In this work we develop the most important parts of a WIM system: characterization of pavement-resin-sensor response, temperature compensation system, analog signal conditioning, digitalization, data processing, storage and data transfer, etc. Besides, very special and refined algorithms had been designed for vehicle classification and calculation of weight, even correcting some common phenomena such as removing spurious axles. Now, all this technology can be produced in Argentina, which is an important innovation and a great advance for the national industry. It has been presented errors study and statistical processing of the results of field measurements, which show adequate accuracy and precision for the development model. It is expected that in production stage the performance of the system can be improved considerably. For example, due to various problems in our project (mainly related to budget restrictions), we had to develop the prototype using two half lane sensors, with the measurement problem that this represents. Now, we are working together with enterprises, so we can implement new measurement sites detecting the whole lane and to achieve a significantly reduction of the errors. Besides, this project also reached the important goal of research and produce knowledge in the area of WIM systems of vehicles, which will allow us to initiate more complex projects, such as the drafting of a technical regulation for dynamic weighing. Given importance which traffic monitoring is taking today in Argentina, we have begun to write a technical regulation draft, in order to normalize the use of these equipment in our country.

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MOBILE SCALES FOR TRAFFIC WEIGHING BASED ON OPTICAL FIBER TECHNOLOGY



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Abstract

We present a project of weigh-in-motion scales that uses photoelasticity. This phenomenon is employed in scales' design to create a periodic signal when a vehicle axle passes over a scale. The axle load is calculated via counting the number of periods of this signal, and the vehicle total weight is then calculated as the sum of the axles' loads. In order to identify whether vehicle tires move on or out of a scale, a two parallel optical channel method is proposed. The porposed design allows one to use optical fiber as the sensitive element of the scales. As a result, the scales are thin (about 1 cm height), light, cheap and may be easily mounted at a road surface. Another advantage is the resistance to overloads. We describe the principles of construction and design, provide calculations for scales' parameters and present the result of laboratory tests.

Keywords: Weigh-in-motion scales, piezooptic dynamometer, photoelasticity, fiber-optic, mobile scales, heavy vehicles**.**

Resumo

Apresentamos um projeto para balanças que medem peso em movimento usando o princípio de fotoelastidade. Este está empregado para criar um sinal periódico de luz quando eixo de veículo passa pela balança. A carga do veículo, distribuida no eixo, está medida via contagem dos períodos de tal sinal e o peso do veículo calcula-se como a soma das medidas obtidas para cada eixo. Para saber se os pneus de eixo estejam entrando ou saindo da balança, emprega-se o esquema de canais óticos paralelos. As idéias do design permitem que seja possível usar fibra ótica como o elemento sensivel da balança. Consequentemente, a balança torna-se fina, leve, barata, estável às sobrecargas, e pode ser facilmente montada em superficil de rodovia. Apresentamos a construção, calculamos seus parâmetros e apresentamos resultados de testes de laboratório.

Palavras-chave: Balança para edição de peso em movimento, fotoelasticidade, fibra ótica, balança móvel para veículos pesados.

1. Introduction

Photoelasticity refers to the appearance of optical anisotropy in initially isotropic objects when they undergo a mechanical stress; its synonyms are photoelastic effect and piezo-optic effect. It has been described in detail by Frocht (1941) and by Shurkliff (1962).

One of the practical applications of photoelasticity is the use of photoelastic dynamometers. The pioneers in this field are Mabboux (1935) and Korolev (1934). A series of dynamometers and other measurement devices that employ photoelasticity were designed and manufactured in the Lomonosov Moscow State University (see Slezinger et al (1976, 1977)). In these series of studies, it was observed that the sensitive element may be an optical fiber (Belitsky (1971)).

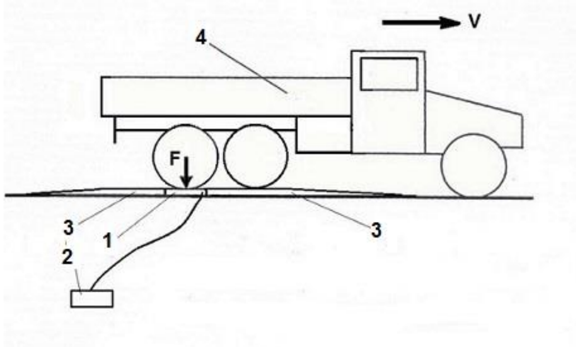
Recent progress in fiber optic technology has allowed for the actual construction and use of fiber optic sensors. Their application range is wide; in particular, they are used for weigh-in-motion (WIM) technology. The state of art in this area is reviewed by Mimbela et al (2003). In the present manuscript, we shall describe our WIM scales with a fiber optic sensor designed for heavy traffic.

Our ideas and certain technological solutions are very similar to those described by Caussignas and Rougier (1999), although there are several essential differences. We are indebted to the referee of our manuscript for pointing our attention to that work. Notably, Caussignas and Rougier also were not aware of our developments (if being judged according to their reference list). The coincidence of ideas of two independent works and their achievements suggest that it is indeed possible to create precise and easy-to-handle mobile scales for heavy traffic with photoelastic fibers as their sensitive element.

2. Design and Operating Principle

Here, we describe the model WIM scale that is being designed for tests in real traffic conditions. The scale (see Figure 1) consists of a fiber-optics dynamometer (1) and an electronic block (2), as well as ramps (3) and other auxiliary items (fasteners etc.). The dynamometer is fastened to the road surface. When a vehicle (4) rides over the dynamometer with velocity V, each of its axles presses down on the dynamometer; let the pressure force be denoted by F.

The dynamometer (Figure 2) contains a single-mode optical fiber (5) set in between two plates that transfer F to the fiber in the direction perpendicular to its axis. This optical fiber is the sensitive element of the dynamometer. The fiber is set in the form of a plane curve like a flat spiral. Each plate consists of two layers. The external layers are metallic sheets (7 and 7a), 3 to 5 mm thick. The internal layers are rubber sheets (6 and 6a), 1 to 2 mm thick. These soft parts serve both to distribute the force uniformly over the fiber and to decrease the sensitivity of the dynamometer, which would otherwise be too high. The layers are glued to each other. Furthermore, the outer layers of the upper and the lower plates are interconnected by metal parts that have high mechanical rigidity in the horizontal direction and low rigidity in the vertical direction. These parts are



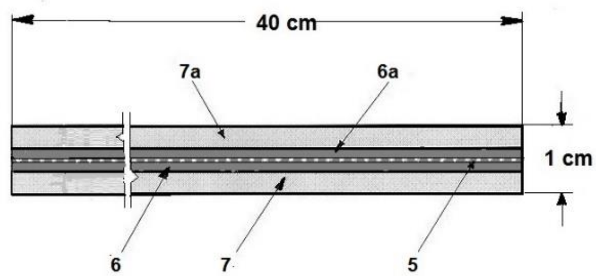


Figure 1 – A truck on the scale

Figura 2 – Vertical section of the scale's load cell

essential for prevention of the mutual displacement of the plates in the horizontal direction due to the forces created by vehicle acceleration or deceleration. The overall thickness of the dynamometer is 1 cm, approximately. The width is approximately that of a road lane – about 6m; the length is approximately 40cm, a little bit more than the size of the contact area with a vehicle's tire, but less than the distance between vehicle axles. With such dimensions, only one axle of a vehicle will be on the scale at any given time.

The fiber receives a linearly polarized light from a semiconductor laser. At the other fiber terminal, there is an analyzer of the light polarization and, connected to it, there is a semiconductor photodetector. When a vehicle passes over the dynamometer scale, it presses down on the dynamometer cover plate and creates a mechanical stress in the optical fiber. The load makes the light in the fiber split into two waves (modes) with different propagation velocities (the photoelasticity effect as explained in the text above). Hence, upon exiting the fiber, the waves' phases are different and, as a result, the outgoing light is elliptically polarized. Its intensity, after it passes through the analyzer, depends upon parameters of the polarization ellipse. Thus, the signal from the photodetector attached to the fiber terminal changes along with the change of the mechanical stress applied to the fiber. Its output is a periodic function (see Equation (1)). All the details and illustrations with regards to the photoelasticity effect in light fibers may be found in Caussignas and Rougier (1999).

Let us note that the number of periods of the output signal depends on the absolute value of the force change but not on whether the force increases or decreases (corresponding to whether a vehicle enters or leaves the dynamometer). In order to identify the force change sign, we employ the method of reverse counting as suggested by Audionis et al (1987). For this purpose, the dynamometer is equipped with an additional optical channel. Its design is identical to that of the principal one, except that the light entering its fiber passes through a quarter-wave phase shifter. As a result, the additional channel signal (U_2 in Figure 4) is offset by a quarter of a period relative to the signal of the principal channel (U_1 in Figure 4), and thus, if the pressure force increases then the maxima of the additional channel signal appear prior to the maxima of the principal channel, and otherwise, they appear afterwards. Thus, by observing whether the main channel signal is ahead or behind of the secondary signal, we can identify whether the force is increasing or decreasing.

The unit marked 2 in Figure 1 contains the laser and all the optical elements except for the optical fiber (that is in the dynamometer). It also contains all the electronic parts of the scale. The block is connected to the dynamometer by a cable housing in which we place the optical fiber that conveys light to the dynamometer fiber and in which we also place the temperature sensor wire that may be necessary for the adjustment and correction of measurements.

The scale may be mounted on a road surface without any specific preparations that might damage the surface. Thus, it can be easily and promptly mounted at almost any desired place on the road.

3. Calculations

The output signal I [A] from the photodetector of the optical channel of a photoelastic dynamometer follows Equation (1) below (see Belitsky (1978)):

$$I = \Phi_L \tau s \{\eta [\cos^2 (\theta_1 - \theta_2) - \sin 2\theta_1 \sin 2\theta_2 \sin^2 0.5(\alpha_o + \Delta\alpha)] + (1- \eta)\} \text{ [A]} \qquad (1)$$

where Φ_L – light source stream [W];

τ – the optical system transparence;

s – the transmission coefficient (sensibility) of the photodetector [A/W];

η – the quality of the optical system;

θ_1– the polarization azimuth of the input light [rad];

θ_2 –the polarization azimuth of the output light [rad];

α_o - the initial phase difference between the waves (modes) [rad];

$\Delta\alpha$ -the phase difference caused between the waves (modes) by the mechanical stress [rad].

The graph of I is presented in Figure 3 for diverse values of θ_1 and θ_2.

From Equation (1), we see that signal depends on the orientation (θ_1, θ_2) of the elements. At the optimal orientation (for example, when $\theta_1 - \theta_2 = \pi/2$, and $\theta_1 = \pi/4$), we get:

$$I = 0.5\Phi_L \tau s \{\eta \sin^2 [0.5(\alpha_o + \Delta\alpha)] + (1- \eta)\} \text{ [A]} \qquad (2)$$

Let us now use Equation (2) to get the numeric value of the signal amplitude A[A]. For safety and cost reasons, we choose a relatively weak laser, which has a light stream, Φ_L, that doesn't exceed 1mW. This light stream is divided nearly equally between the two optical channels and, therefore, we will introduce the factor 0.5 in Equation (2). The optical fiber is transparent, and the light loss occurs, mostly, in the polaroid. For polaroids available at a reasonable price, one can expect the optical system transparence $\tau \approx 0.3$. The transmission coefficient s of the Germanium photodiode is roughly equal 0.7A/W for the light with the wave length used in the dynamometer. The quality η of the system as a whole is determined essentially by the quality of

the polaroid. The value of η is calculated from the formula $\eta = (I_{max} - I_{min}) / I_{max}$. Here I_{max} and I_{min} denote the extreme values for the signal that can be received at the exit of a given polarization-optical system. Our experimental data obtained from testing a model of the dynamometer lead to $\eta \approx 0.8$. Now, from Equation (2) and with the numerical values of the parameters presented above, we get that the signal amplitude, A, is approximately 0.04mA. This is a significantly large signal. It is enough for
successful counting of periods of the signal by simple and cheap electronic devices. Let us emphasize once more the importance of the orientations of the optical elements: the calculations present above have been made for the optimal orientation.

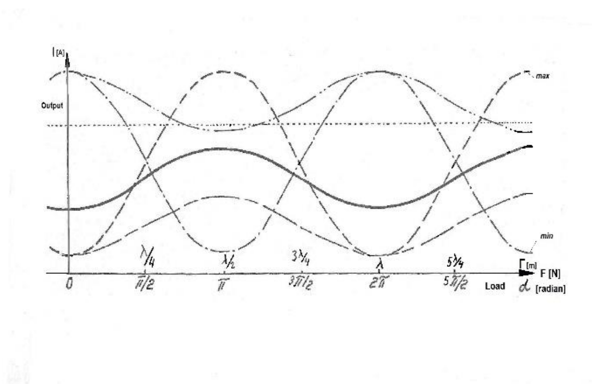


Figure 3 –Graphical illustration to Equation (1)

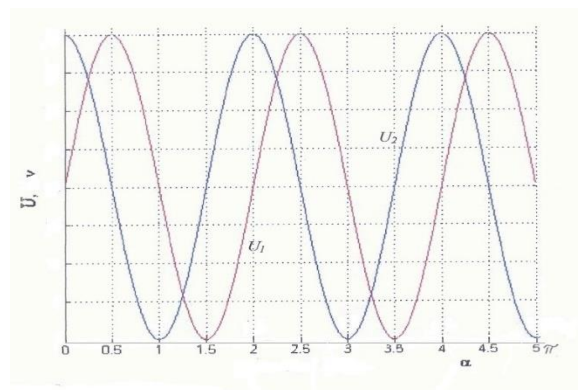


Figure 4 – The output signals of the optical channels

For the next calculations, we shall employ the following formula (see Frocht (1941)):

$$\Delta\alpha = 2\pi L \, \text{б} / \sigma_o^{1.0} \quad [\text{rad}] \qquad (3)$$

where L[m] is the length of the optic fiber that receives the load, б [N/m^2] is the mechanical stress in the fiber optics, $\sigma_o^{1.0}$ [N/m] is the optical characteristic of the material. It equals to the amount of uniaxial mechanical stress necessary to be created in the cross-section of a transparent material of a unit length (1m) along the light propagation direction, so that the optical distance difference Γ of the light waves (modes) would be equal to the length of the light wave λ. We use fiber-optic cables that are used in optical communication. In this kind of optical fiber, the light conducting core is made of molten quartz (quartz glass). The optical properties of this material are known (see Landolt-Börnstein (1962)). Since the aim is to achieve the maximal possible fiber-optic transparency, we use the light with the wave length $\lambda = 1.31$ μm. For this value of λ, Landolt-Börnstein (1962) gives $\sigma_o^{1.0} = 385{,}000$ N/m.

We can assume that the value of б is approximately equal to the air pressure in vehicle tires, p[Pa].
Let us now assume that surface of the dynamometer receiving the load is a rectangular $B_1 x B_2$ and that the measured force F spreads equally across it, creating the pressure $p = F / (B_1 B_2)$. The

length L of the optical fiber that is compressed by F is B_1B_2/h, where h[m] is the space between fiber spiral loops. These expressions and Equation (3) give the relation

$$\Delta\alpha = 2\pi F / (h\sigma_o^{1.0}) \ [\text{rad}] \qquad (4)$$

that proves that phase difference, $\Delta\alpha$, and, subsequently, the output signal of the dynamometer is independent of the area of the load surface. The same calculation holds true for any geometry of the loaded surface independently of the place of the dynamometer surface where the force is applied.

We shall now calculate the force F_1[N] corresponding to one period of the output signal. From the definition and Equation (4), we get that $F_1 = h\ \sigma_o^{1.0}$ [N]. For our construction, we choose h=0.01m, hence F_1 =3850 N. We shall need this value below but, at the moment, we conclude from the obtained results that the dynamometer sensitivity may be modified by choosing the appropriate density of the optical fiber pattern.

Let us now estimate the resolution of the scale under our consideration. The electronic apparatus of the scale is made in such a way, that it outputs four impulses in a single signal period, meaning the discretization of the measurement is $F_{min} = F_1/4 \approx 960$ N. Next let F_{max} denote the maximal force that a truck axle can produce and let us assume that it is $3*10^5$ N. Then, the maximal number of the impulses of the scale's electronic signal is $n_{max} = F_{max} / F_{min} \approx 300$, and accordingly, the scale's resolution is about 0.33%. This resolution is sufficient to enable the scales to reveal a truck overload.

With regards to the spectrum of the electric output signal, we note the following. Its lowest bound is statics, i.e. the spectrum's smallest frequency is the one corresponding to the case when the vehicle stops over the dynamometer. The highest value is determined by the speed of counting impulse signals: $f_{max} = n_{max} V / 3.6\ B_2$[Hz] , where n_{max} is the maximal number of impulses of the output signal, B_2 is the length measured along the vehicle motion direction, of the area of the contact between the tire and the road, and V[km/h] is the vehicle's velocity. Plugging into the formula V=50km/h, B_2 = 0.25m, n_{max}=300, we get f_{max} is approximately 20 KHz. This frequency isn't a challenge for modern electronics.

To show that the dynamometer is stable to overloads, we present the following argument. First we observe that the maximum mechanical stress in the fiber-optics cannot be larger than the maximum allowed air pressure in a wheel tire; so, we take $б_{мax} = 8.5*10^5$ Pa. In the dynamometer design, we intend to use optical fibers with a plastic covering. According to the manufacturers, the plastic tensile and compressive strengths are about $1.3*10^8$ Pa and $3.6*10^8$ Pa, respectively, which is much larger than $б_{мax}$. The strength of the quartz glass fiber is even greater.

Let us turn our attention to the errors in measurements. They are dynamic errors, static errors, errors caused by aerodynamic forces acting on the vehicle and errors caused by temperature changes.

Dynamic errors occur due to the impact of the wheels against the dynamometer. To diminish the impact (and prevent possible traffic accidents) we suggest coupling the dynamometer with ramps. Since the dynamometer height is about 1cm then a ramp of the length of 5 meters should provide a safe inclination. We calculated that, at the velocity 50km/h, a wheel impact will cause the measurement deviation of less than 3%.

Static errors occur due to the deformation of the axle springs. The point here is that the spring of the axle that is over the dynamometer is more deformed than the springs of the other axles. Hence, the vehicle weight is not distributed equally over the axles. This effect may be eliminated if we construct a long ramp so that all axles of a tandem drive axle would be on the same level as the one that passes over the dynamometer. We are left with the slight change in wheel pressure due to the mild inclination of the whole truck when mounting the platform. According to our estimations, the error caused by this effect doesn't exceed one percent of the measured weight.

The aerodynamic force raises a vehicle in motion and, thus, could alter the weight measurement. This error may be eliminated, if and when necessary, by measuring the wind velocity then measuring the vehicle's velocity and making adequate corrections to the measured weight.

The temperature affects the measurements because it changes the photoelasticity of fiber-optic material. This change, according to Landolt-Börnstein (1962), is 0.1% for each 1°C. We can assume the dynamometer temperature will change by a maximum of 50°C. The resulting measurement error will be about 5%. This calls for corrections of the dynamometer measurements in accordance to a temperature sensor. Such corrections may be easily implemented in the opto-electronic block of the scale.

Besides the systemic errors addressed above, there may be a noise in the output signal caused by diverse factors, like wheel vibration, for example. The effect of this is the presence of local "wrong" extrema in the output signal. With regards to this, we note that the employment of two channels (that has been suggested for the reverse counting as described in Section 2) may help to identify them because when a true extremum is present in one of the channels it is necessarily absent in the other one.

4. Experiments

We manufactured and tested scales of diverse structures with diverse optical elements in laboratory conditions. Figure 5 shows our Model 5 loaded with weights. The model was built using a single-mode optical fiber with a thin plastic covering. (The previous four models had shown unsatisfactory results, the reason for that was the thickness of the fiber covering.) 6.5-meter-long piece was set in a flat spiral form in between two aluminum plates. We used a semiconductor laser ($\lambda = 1.55$ µm), an infra-red light polarizer film manufactured by ZOMZ (an optical equipment plant in Russia), and a AlGaAs photodetector manufactured by Infrared Associates Inc.

Figure 6 shows the results of tests of Model 7 that is similar to Model 5 described above. In Model 7 we use a Ge photodetector and a 1m piece of optical fiber that forms a single spiral loop (of a “U”-like form) between the plates. (In Model 5, the spiral loops were not uniformly distributed. Also, with a shorter fiber, we easily succeeded in eliminating its internal tension.) The upper chart of Figure 6 shows an initial part of the output signal, and the lower chart shows the divergence from the mean value. The standard error (σ) is 0.54% of the signal diapason. When we increased the load, we succeeded in determining the period of the output signal. It is 26.5N. It is close to the theoretical calculations of 25.7N.

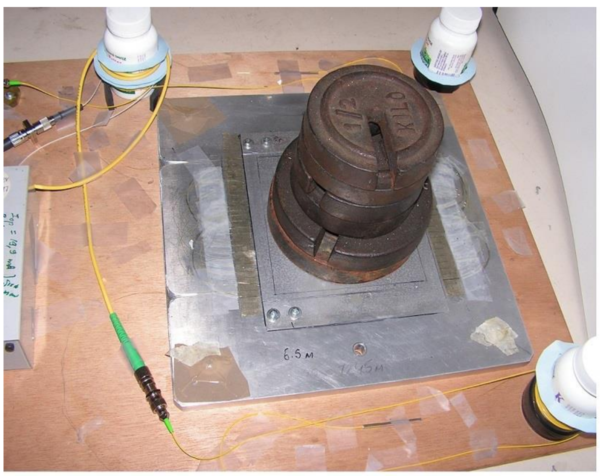


Figure 5 –Photoelastic load cell. Model 5

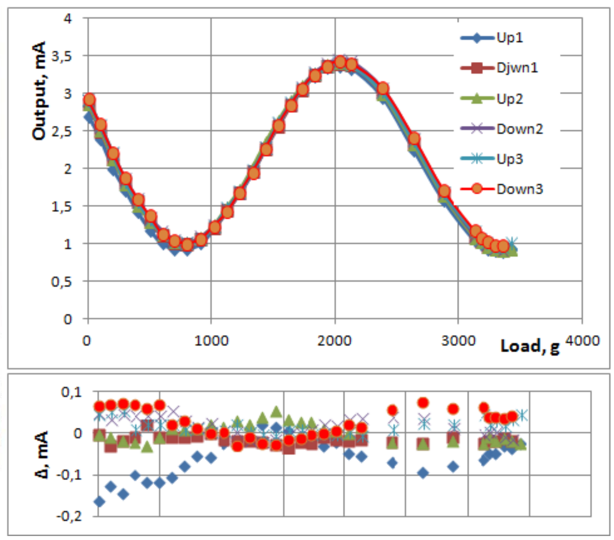


Figure 6 – Calibration of Model 7

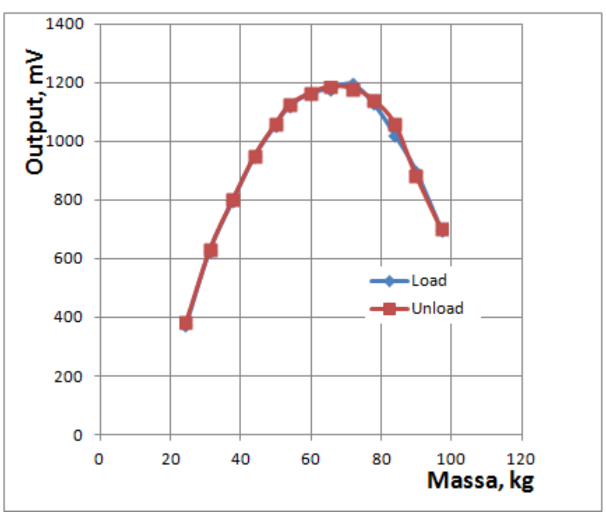
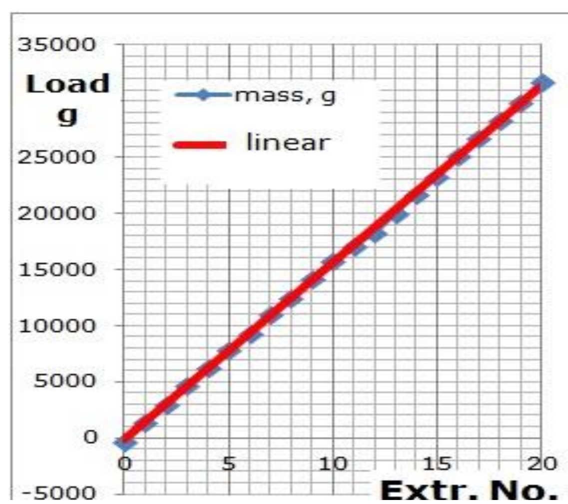
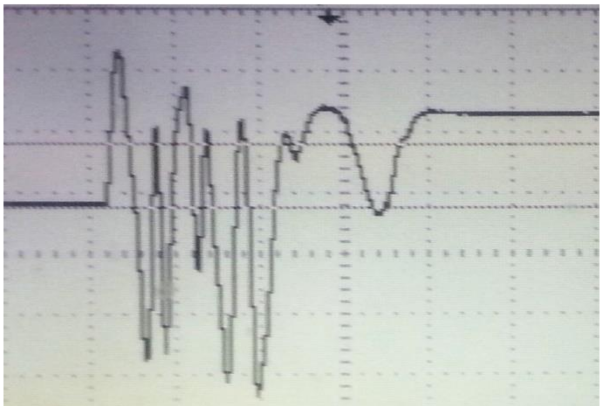


Figure 7 – Calibration of a model with rubber gaskets



Iodel 6) under a
heel

Figure 8 – The dependence of the number of signal extrema on the load (Model 13)



We also made several models with rubber gaskets. As we have stated above in the text, the gaskets diminish the force transferred to the fiber optics. To be able to apply large forces in laboratory conditions, we used a screw press with a spring. The limitation of the press construction did not allow us to apply the forces needed to see a full period of the output signal. By extrapolation of the available results (shown in Figure 7), we estimated that the signal period is approximately 1,500N. This is much larger than the period obtained for models without rubber gaskets, and thus, confirms our expectation that the scales designed as described in Section 3 above will be applicable for heavy trucks. However, the empirical period is almost twice as small as its theoretical counterpart. We think that the reason for this is that the rubber of the gasket was not sufficiently soft. As a consequence of this, the fiber could not penetrate deep into the gasket, the upper and the lower gaskets did not touch each other and thus, the fiber suffered a load that is larger than that taken in theoretical calculations.

Model 13 was loaded with a weight large enough to produce 10 periods of the output signal. This was necessary to produce the statistics that confirm that the number of periods depends linearly upon the applied load (see Figure 8). The standard deviation is about 0.61% of the diapason. We note that in real traffic conditions, the average number of the signal periods is approximately three times the number of periods in this experiment. We observe that in Model 13 we succeeded in distributing 9 loops of the fiber.

We also manually rolled a 20.2kg wheel over the dynamometer of Model 13. The output signal is in Figure 9. The leftmost flat portion corresponds to the unloaded state, and the rightmost one to the state when the whole wheel is on top of the dynamometer plate. Passing over the plate created 6 clear periods and one more period that is not sharply expressed. The dynamometer signal period is 3.15kg. So, the scales gives us that the weight is about 20.4kg.

Figure 10 shows the test of durability of our construction and conveys an idea of the dynamometer dimension for weighing passenger cars.

5. Conclusions

We conducted theoretical and experimental research aiming for construction of a WIM scale with a photoelastic dynamometer in which the sensitive element is an optical fiber.
We suggested the design that allows the WIM scale to be mounted and dismounted at almost any place on a road and without any significant damage to the road surface.
The scale employs the method of reverse counting that allows us to enhance its precision.
In order to achieve a desired sensitivity of the scales, we suggest using rubber gaskets and choosing the appropriate distance between fiber filaments.
The next step will be to construct a model with full-scale dimensions and check its functioning in real traffic conditions.

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STRAIN GAUGE BASED WIM SENSOR PERFORMANCE IN LOW SPEED APPLICATONS



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Abstract
This paper reports on the performance of strain gauge based Weigh-In-Motion (WIM) strip sensors for low speed applications.
There is a need for precision low and medium speed strip sensors for WIM applications. These include: weight-based Electronic Toll Collection (ETC), screening, freight terminals, rail yards, and seaports. The strip sensors cost less than traditional platform scales and require no drainage or ongoing maintenance.
The data collected at the MnROAD and Puerto Cortés' sites demonstrate that the strain gauge based strip sensors perform well in low speed applications. The strain gauge strip sensor and instrumentation easily met gross weight accuracy requirements of ASTM 1318 Type III and Type IV and COST 323 A(5). The standard deviation of all runs (n=392) was 1.2%, which dropped to 0.7% when considering only fully loaded (>60000 lb) trucks (n=201).

Keywords: Weigh-In-Motion, WIM, Low Speed, Strip Sensor, Port, Toll, Tolling, Freight, traffic data collection, strain gauge, ASTM 1318, COST 323.

Résumé
Cet article présente les performances des capteurs de type barreaux pour le pesage en marche dans le cas des applications à faible vitesse.

Il y a un besoin de précision pour ce type de capteurs dans les cas de vitesses moyenne et basse pour les applications du pesage en marche. Nous pouvons citer : le télépéage fonction du poids (ETC), les gares de triage et les ports maritimes. Ces capteurs de type barreau coûtent moins cher que les balances traditionnelles et ne nécessitent pas de drainage ou de maintenance.

Ces barreaux ont démontré une haute précision à faible vitesse, lorsqu'ils ont été installés sur les sites MnROAD et Puerto Cortés. En effet, la précision obtenue a été de type ASTM 1318 Type III and Type IV and COST 323 A(5).
Les données ont également montré aucune incidence sur la précision de la part des conditions environnementales ou des changements de température.

Mots-clés: Pesage en marche, WIM, Basse vitesse, capteur barreau, port, péage, fret, enregistrement de données de traffic, jauge, ASTM 1318, COST 323.

1. Introduction

There are many reasons why it is necessary to obtain accurate weights of cargo. Trucking companies tend to overload trucks to reduce the operating/fuel costs of transporting goods. Companies shipping goods on container ships may claim a lower than actual weight to reduce the price of shipping their cargo. The incorrect container weights cause a ship to use excess fuel and may cause uneven loading. Regulations require container weights to be verified before hoisting.

There is a need for a low speed WIM system that has the following features:

- Low initial purchase price (approximately 50% of the price of traditional steel framed weigh bridges).
- Low cost installation (install into slots that are cut into the roadway).
- Minimal installation time (can be accomplished in less than a day).
- Low maintenance and operating costs (no need to clean debris out of scale pits).
- No need for drainage systems (this is especially important for large multi-lane applications like border crossings or weight based tolling applications).

A low speed WIM sensor configuration is now available that meets these requirements for weight based tolling applications, shipping ports and other applications requiring low speed WIM. The system offers low cost strip sensors, low cost installation and does not require a drainage system. The system consists of Intercomp Strip Sensors that offer high accuracy and trouble free operation paired with the Intercomp WIMLOGIX CPU or other electronics.

Intercomp Company was founded in 1978. Throughout its history the company has specialized in designing and manufacturing static and dynamic high capacity weighing systems for the transportation industry. Intercomp's fully electronic strain gauge technology was used to develop one of the first fully electronic digital wheel load scales used for direct enforcement of overweight vehicles. Similar, but higher capacity and greater precision scales were designed for weighing NASA Space Shuttles, military and commercial aircraft, and over the road trucks. Since 1992, Intercomp has been supplying static and dynamic systems to the Unites States and Foreign militaries for weighing vehicles and cargo in support of loading aircraft, ships and rail for rapid deployment purposes. Dynamic designs, including medium and high speed systems, have been refined for use in applications ranging from POE's (ports of entry), border security, tolling and data collection.

2. Strip Sensor

The in-road weigh sensors are based on high performance strain gauge technology. They operate over a wide range of environmental conditions and roadway surfaces. The sensors are available in lengths of 1.5, 1.75 and 2 meters.

Although there are advantages and disadvantages to every method of measuring a load, there is a reason that precision scales use strain gauge based load cells. Strain gauge based scales function statically unlike piezoelectric sensors. This means they can even be calibrated with static loads because they operate on the principle of measuring the change in resistance, as they are elongated, in relation to the strain of the base (load cell) material. Temperature compensation ensures that strain gauge scales remain accurate over the temperature extremes.

The new high accuracy LS-WIM system is the result of 35 years of experience in using a scientific approach to load cell design, scale design, and algorithm development. The use of highly accurate load cells allows every subsequent step in the weighing process to take advantage of the initial high accuracy.

The system generally consists of strip weigh sensors placed in the roadway, loop sensors and Intercomp's WIMLOGIX weigh in motion module (CPU for signal conditioning), or third party controller and operating system.

3. Methods

The testing for this paper was completed at two locations using nine different vehicles. The vehicles ranged from a three axle solid body truck to a six axle tractor/trailer. The vehicles passed over the Intercomp strip sensors at speeds that ranged from 2-35 miles/hour (mph) (3-56 km/h) with about 50% of the runs 2-10 mph (3-15 km/h). The trucks passed over the strip sensors and their gross vehicle weights were recorded. The data is presented in this paper.

3.1 Evaluation Test Sites

The test vehicles for the MnROAD test site were weighed on a static "CAT Certified Scale," before testing on the Intercomp strip sensors. The MnROAD weight truck of known weight was used to calibrate the strip sensors. Test vehicles were weighed as they passed over Intercomp strip sensors. The output from the strip sensors was conditioned by the Intercomp WIMLOGIX CPU.

Most of the testing (351 of 392 runs) was completed at the Minnesota Department of Transportation test track (MnROAD) in Albertville, Minnesota, USA (Figure 1). Intercomp has been testing the Intercomp strip sensors on this site for five years.

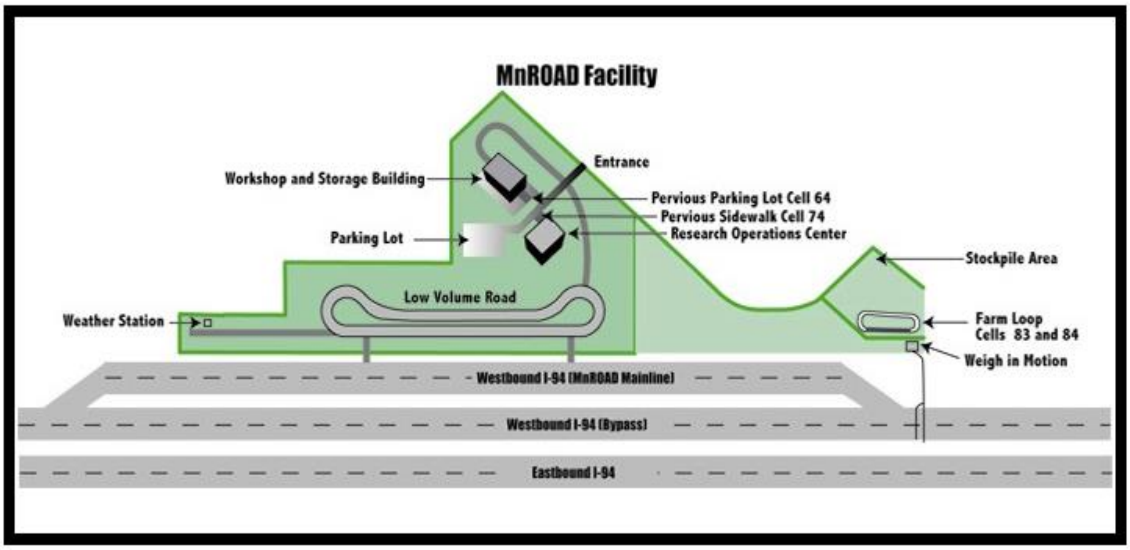

Figure 1 - MnROAD Testing Facility Showing Low Volume Road (Loop)

Testing was also done recently at the Puerto Cortés, Honduras, shipping port (Figure 2). The Low-Speed-WIM (LS-WIM) site uses eight Intercomp Strip Sensors. The LS-WIM system is used to weigh shipping containers. To test the LS-WIM system four random containers were placed on trailers and weighed as they passed over the strip sensors at speeds ranging from 2-10 mph (3 to 15 km/h).

Calibration was performed using a single truck after weighing on a reference static scale. While performing test runs with the first truck, it was noticed that the reference weight for the calibration truck was suspect. Rather than recalibrate and restart testing, a correction factor of 1.7% was used to correct all of the weights.

Figure 2 - The Shipping Port Test Site at Puerto Cortés, Honduras

A typical Intercomp LS-WIM site is shown in Figure 3. Additional sensors may be added to increase the accuracy of the system. The LS-WIM system at MnROAD used 8 sensors and the port LS-WIM system in Honduras used 8 sensors.

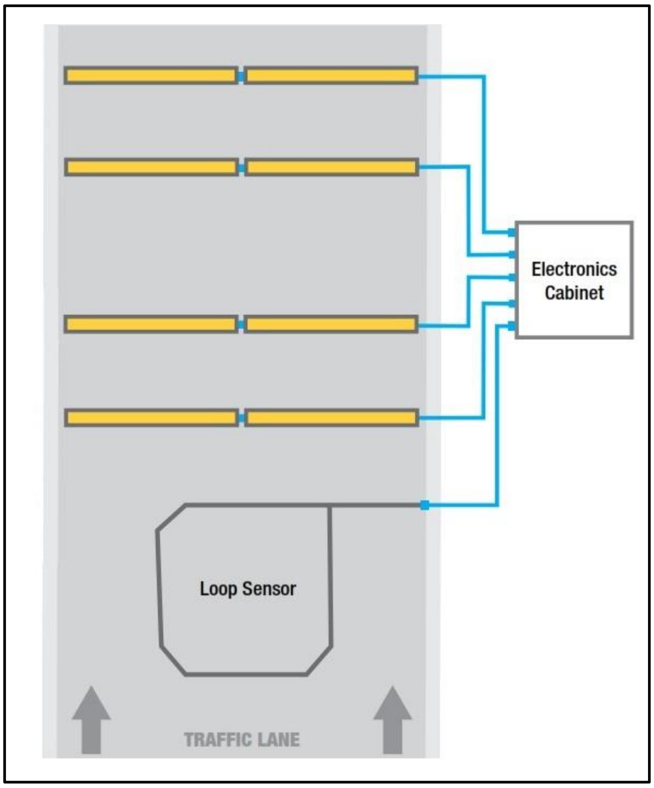

Figure 3 – Typical Strip Sensor Configuration Using 8 Sensors

3.2 Sample Test Vehicles

Vehicles with differing weights and classifications were used while collecting data for this paper. Figure 4 shows a sampling of the test vehicle axle configurations and classes, which illustrates the variety of vehicles used to widen the data set.

Figure 4 – Sample Test Vehicles

4. Results

The MnROAD installation was evaluated using 5 different trucks for a total of 351 runs. The tests runs were performed between 2 and 35 mph (56 km/h). Data was limited to less than 10 mph (16 km/h) for the ASTM Type IV analysis (n=150). The Puerto Cortés Honduras installation was evaluated using 4 different trucks for a total of 41 runs. No formal ASTM 1318 Type approval or COST 323 Classification was sought. The specified number of runs and other parameters for a formal classification was not followed; however, the data was analyzed per the performance standards and is now presented in these formats. The data at both sites is consistent with a COST 323 A(5) classification and well within ASTM 1318 Type I, Type II, Type III and Type IV performance requirements.

Dynamic versus static truck weights are presented in figure 5. The graph shows the 9 test trucks and 392 runs at both sites. A linear regression line is fit to the data and 10% error bands are also included in the graph. No test runs were outside the 6% ASTM 1318 Type III tolerance limit.

Figure 5 – Dynamic (LS-WIM) Weight vs. Static Weight (n=392)

The Intercomp WIM system may be assessed in accordance with COST 323 classes A(5), B+(7), or B(10) for example. The COST 323 standards are covered in COST 323 "Weigh-in-Motion of Road Vehicles," Final Report, APPENDIX 1, European WIM Specification, Version 3.0, August 1999. The COST 323 standards have much in common with ASTM 1318. Systems are designated by seven Accuracy Classes: A (5) through E, via performance requirements with associated calibration procedures and road conditions. Environmental conditions of testing (range of dates between tests etc.) and initial versus verification testing play a significant role in evaluating statistics for classifying.

Data collected at MnROAD and the port in Honduras (Puerto Cortés) met the COST 323 A(5) accuracy classification for gross vehicle weight. This initial verification was confirmed using the 5 trucks and 351 runs at MnROAD, and 4 trucks and 41 runs at Puerto Cortés. A summary of the data is shown in table 1 (MnROAD) and table 2 (Puerto Cortés) in COST 323 format.

Table 1 - MnROAD Installation Data Presented in COST 323 Format

Strain Gauge Strip Sensors	Number	Mean	Standard Deviation	COST 323
Entity	n	(%)	(%)	(Class)
Gross Weight	351	0.4	1.3	A(5)

Table 2 - Puerto Cortés Installation Data Presented in COST 323 Format

Strain Gauge Strip Sensors	Number	Mean	Standard Deviation	COST 323
Entity	n	(%)	(%)	(Class)
Gross Weight	41	-0.3	1.0	A(5)

WIM systems may also be assessed according to ASTM standards, namely ASTM E 1318-09 Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Methods. Systems designated by Type according to Application: Types I, II, III, and IV. Type IV is a meant for low speed enforcement applications. Minimum Accuracy Level (95% conformity) is required for each Type. These are all Pass-or-Fail Tests.

A summary of the data is shown in table 3 (MnROAD) and table 4 (Puerto Cortés) and presented as 95% compliance data against ASTM 1318 Type III requirements. Also shown is the data presented with Type IV requirements.

Table 3 - MnROAD Installation Data Presented in ASTM 1318 Format

Description	n	ASTM 1318 Type III	Intercomp Strip Sensors	ASTM 1318 Type IV	Intercomp Strip Sensors
Gross Weight					
All	351	+/- 6 %	+/- 2.5 %*		
GVW > 60000 lb (27200 kg)	150			+/- 2500 lb	+962/-1294 lb**
* 2 Standard deviations shown. No runs outside tolerance.					
** All runs included. No runs outside tolerance.					

The sample size was reduced above for the Type IV test that excludes data above 10 mph. 200 runs were between 10 and 35 mph.

Table 4 - Puerto Cortés Installation Data Presented in ASTM 1318 Format

Description	n	ASTM 1318 Type III	Intercomp Strip Sensors	ASTM 1318 Type IV	Intercomp Strip Sensors
Gross Weight					
All	41	+/- 6 %	+/- 2.0 %*		
GVW > 60000 lb (27200 kg)	32			+/- 1100 kg	+643/-833 kg**
* 2 Standard deviations shown. No runs outside tolerance.					
** All runs included. No runs outside tolerance.					

The sample size was reduced in the Puerto Cortés data set above as one of the trucks was below the 60000 lb (27200 kg) minimum weight for Type IV analysis.

The standard deviation of the GVW error for the truck runs was 1.0% (Puerto Cortés) and 1.25% (MnROAD). ASTM 1318 requires 95% of the runs to meet the stated tolerance. For Type III, the strictest class for high speed WIM, 95% of the GVW recordings must be within 6% of actual weight.

Similarly, ASTM 1318 Type IV requires the results to be within a weight tolerance for each weight class. For trucks with GVW > 60000 lb (27200 kg), the tolerance is +/- 2500 lb (1100 kg). Lighter trucks are not considered per the standard. However, even when including vehicles lower than this weight, all trucks tested were within the tolerances.

For the MnROAD site, up to 5% of the runs are allowed to be outside the tolerance bands or 17 runs (of 351) for the Type III classification and 7 runs (of 150) for the Type IV classification. For the Puerto Cortés site, 2 runs (of 41) could be outside the tolerance bands for the Type III classification and 1 run (of 32) for the Type IV classification (a formal classification would require more runs). In this study, all of the runs were within the tolerance.

5. Discussion

The data collected at the MnROAD and Puerto Cortés sites demonstrates that the strain gauge based strip sensors perform well in low speed applications. The strain gauge based strip sensor and instrumentation met gross weight accuracy requirements of ASTM 1318 Type III and Type IV and COST 323 A(5).

Neither of the test sites had ideal pavement conditions. Some of the trucks had leaf spring suspension and several had lightly loaded trailers, which tend to bounce more and can be difficult to weigh accurately. If the data set were limited to trucks with a gross weight of over 60000 lb (27200 kg) (3 trucks at 2 sites and n=201), the standard deviation of the error would drop to 0.7%. Heavily loaded truck accuracy is more important for enforcement as evidenced by the ASTM Type IV standard only referencing trucks above 60000 lb (27200 kg).

The data gathered in this study suggests that with optimum road conditions and loaded trucks, the accuracy of the strain gauge strip sensors in low speed WIM applications could be +/-1%. Further testing is needed to demonstrate the accuracy potential of the strip sensors.

6. Conclusion

The strain gauge based strip sensor was shown to perform well in low speed WIM applications. The evaluations were performed at the Minnesota Department of Transportation's MnROAD research facility (USA) and Puerto Cortés (Honduras).

Accuracy was determined using 9 test trucks and a total of 392 runs. GVW accuracy was determined to meet or exceed ASTM 1318 Type III and IV and COST 323 A(5) class accuracy requirements. Accuracy approached +/-1% with loaded trucks at both sites.

Previous reports on the strain gauge based WIM strip sensor demonstrated accuracy exceeding ASTM 1318 Type III and the COST 323 A(5) class at highway speeds. The data also showed no impact to accuracy from environmental conditions, temperature changes, or wear from several million vehicles.

The strip sensor is well suited for low speed applications such as rail yards and seaports; and high speed applications such as traffic data collection, monitoring bridge loads, and weight enforcement.

The authors would like to acknowledge the support of MnROAD and its operations staff.

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TEMPERATURE PROPERTIES OF WEIGH-IN-MOTION SYSTEMS

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Abstract
The use of Weigh-in-Motion systems for direct enforcement depends, first of all, on their high and constant accuracy under variable measurement conditions. Among climatic influencing factors, the pavement temperature turns out to be the most significant one. This paper presents a detailed analysis of this phenomenon. An analysis was carried out for two WIM systems fitted with polymer and quartz load sensors. The temperature variability and its influence on the weighing error was experimentally investigated. Certain methods for the correction of the influence of pavement temperature, based on the WIM site temperature model and on the system calibration performed at several temperatures, were proposed. The influence of a non-uniform temperature distribution along the WIM site, which is of particular significance in multi-sensor systems, was considered. Furthermore, the influence of temperature distribution along a load sensor was analysed. The last issue is described for the first time. It was also demonstrated that the multi-point temperature correction, taking the temperature distribution along a load sensor into consideration, enables the weighing error to be limited to the level of 1%–1.5% over a wide temperature range, from -20°C to +30°C.

Keywords: Weigh-in-Motion systems, temperature properties, axle load sensors properties, temperature correction.

Résumé
La mise en œuvre des systèmes de pesage en marche pour le contrôle sanction automatisé est principalement conditionnée par leur précision variable dans des conditions de mesure changeantes. La température de surface de la chaussée s’avère être l’un des facteurs climatiques ayant le plus d’effet sur la precision de la mesure. Ce papier contient une analyse détaillée de ce phénomène. Deux systèmes WIM munis de capteurs de pression polymères et quartz ont fait l’objet de cette analyse. Nous avons proposé différentes méthodes pour compenser l'effet de la température. Ces problèmes ont été étudiés et décrits pour la première fois. Dans la dernière partie de l'étude nous avons démontré que les points de vue actuels concernant l’étalonnage des systèmes WIM doivent être revus.

Mots-clés: Systèmes de pesage en marche, effet de la température, propriétés des capteurs de mesure de charge des essieux, correction de température.

1. Introduction

In the initial period of the development of Weigh-in-Motion systems, the variable axle load of a moving vehicle was considered to be the main cause of the large inaccuracy of weighing results. However, a more insightful study has demonstrated that there are several additional factors interfering with the measurement (Burnos & Ossowski 2015). This is not the only difficulty in the analysis of this phenomenon since the present WIMs are a group of measuring systems, widely diversified in terms of their construction. Within this group can be distinguished Low Speed WIM, High Speed WIM and Multi-Sensor WIM systems, and each of them can be equipped with various load sensors, such as polymer, quartz, bending plate, capacitive or fiber-optic. This generic and technological diversity is the reason they differ in their metrological properties, and therefore their description is not an easy task. Previously made attempts did not provide a satisfactory answer to the basic questions of how the inaccuracy of weighing results should be assessed, and what minimum level of this inaccuracy is currently achievable. The answer to these question is associated with selecting an optimal system structure and with quantitative assessment of the influence of disturbing factors on the accuracy of weighing results, in particular the short- and long-term influence of the pavement temperature variation and the vehicle speed.

The goal of this paper is to achieve progress on closing the gap within the scope of analysis and assessment of thermal properties of WIM systems equipped with quartz and polymer load sensors. We present a quantitative assessment of the influence of pavement temperature on vehicles' weighing error caused by the intrinsic properties of the load sensors and the thermal properties of the pavement. In particular, the long-term accuracy assessment of WIM systems equipped with both kinds of sensors has been shown. The characteristics describing the change in system error as a function of temperature have been experimentally determined. We will also present the effects of temperature gradient occurring on a multi-sensor site and discuss the known methods for thermal phenomena compensation in WIM systems. New methods for multi-point correction and calibration will be presented. In the final part of this paper we will demonstrate that currently adopted recommendations from COST 323 concerning temperature stability during the system calibration and testing its accuracy are not correct. Precise, Multi-Sensor WIM systems intended for enforcement should be calibrated and tested over a wide range of temperature variation similarly as they are currently tested over a wide range of vehicle speeds (the pre-weighed vehicle method). Such an approach will provide complete information about the system accuracy, regardless of weather conditions.

2. Literature review

Ongoing research on WIM systems is aimed at their application for enforcement purposes. Practical implementation of this idea is subject to two conditions: defining detailed procedures for legalization and metrological control of WIM systems (test conditions), and defining technical requirements for such WIM systems. The second problem ensues from the high sensitivity of WIM systems to weather conditions, environmental influences and factors directly associated with the weighed vehicle and its behaviour at the WIM site (Jacob & Feypell-de La Beaumelle 2010). One of the main factors having the most significant effect on the WIM system’s accuracy are the pavement temperature changes.

At the beginning of the twenty-first century, Papagiannakis, Johnston and Alavi carried out studies on piezoelectric sensors. In one such study (Papagiannakis, Johnston & Alavi 2001), they focused on laboratory evaluation of the fatigue characteristics of piezoelectric WIM sensors under wet and dry conditions. In another paper written by the same authors

(Papagiannakis, Johnston, Alavi, et al. 2001), the results of the field evaluation of WIM sensors of two manufacturers, namely Vibracoax (VC) and Measurements Specialties Incorporated (MSI), were presented. In these experiments the influence of the pavement temperature on the sensors' output signal was investigated. Studies have shown that raw signal amplitude depends on the temperature sensors installed in the asphalt concrete pavement. Concurrent with increasing pavement temperature, the signal amplitude of the MSI sensors increased, while it decreased for the VC sensors.
Temperature properties of WIM sensors are also addressed in (HITEC 2001). The paper describes the laboratory and field tests of the RoadTrax BL sensor manufactured by MSI. During tests all the examined sensors exhibited an increase in signal amplitude with increased temperature of asphalt concrete pavement. The coefficient in this relationship expressed in volts per degree Celsius is as high as 0.162.
The strong influence of temperature on weighing error in WIM systems employing piezoelectric polymer sensors is also emphasised in the paper (Jiang et al. 2009). The results presented confirm that the polymer sensor and the ceramic sensor are considered to be temperature sensitive, while the quartz sensor is insensitive to temperature.
A similar conclusion is reached by Vaziri in his PhD thesis (Vaziri 2011) and further publications (Vaziri et al. 2013). The aim of this research was to explore the behaviour of WIM piezoelectric sensors under different environmental conditions. The author conducted field tests on two WIM sites involving three types of load sensors: quartz (Kistler), polymer piezoelectric (MSI) and ceramic piezoelectric (Electronique Controle Mesure - ECM). Unfortunately, the reliability of the presented results seems to be very limited because the author measured the temperature of the air instead of the pavement and only within a small range (8 - 16 Celsius).
The temperature properties of WIM sites were also examined by the authors of this paper. Since 2005, a series of test has been performed at a Multi-Sensor WIM site equipped with 16 polymer axle load sensors provided by MSI (Burnos et al. 2007). Long-term tests clearly showed a strong relationship between pavement temperature and weighing results. A model of this relationship was first introduced by Burnos in 2008 (Burnos 2008) and further investigated in (Gajda et al. 2012).
From the data obtained during all the aforementioned works it was not possible to determine if the increase in sensor's output amplitude is caused by a decrease in pavement stiffness or due to the thermal properties of the sensor itself. Such a study for polymer sensors was undertaken by the authors and described in (Gajda et al. 2013) where the results of tests in a climatic chamber, as well as of long-term tests at the WIM site, were presented. A quantitative assessment of the temperature impact on the sensor itself and on the asphalt concrete pavement stiffness were described.

Almost all the mentioned works concern exclusively polymer sensors. One field that still need more investigation is the thermal properties of quartz sensors. For instance, Kistler gives a temperature coefficient of sensitivity –0.02%/°C (Kistler 2016). This value, however, refers solely to the piezoelectric material used, and does not take into account temperature effects occurring after the sensor installation in the pavement. It was therefore justified to examine such sensors at the installation site, and this is also described below in this paper.

3. Sensor intrinsic errors

The primary objective of experimental investigation was to determine the influence of temperature on changes of the piezoelectric sensor equivalent parameters and, consequently, on changes in the accuracy of weighing results. Experiments were carried out in a climatic chamber and at an WIM test site installed in a roadway. The research has been described in detail in (Gajda et al. 2013).

The measurements were made for two sensors of the same type. In the first case only the sensor was placed in the chamber, whereas in the second case the sensor was placed with the cable connecting it to the measuring system. The measurement results of the sensor equivalent parameters are shown in Figure 1. The measurements were performed over a temperature range from –30°C to +50°C, according to the requirements of standard (ASTM 2009).

The weighing error arises from the difference between the actual sensor temperature value and the reference temperature value at which the WIM system was calibrated (the reference temperature was +20°C). The relative value of error is computed from relation (1).

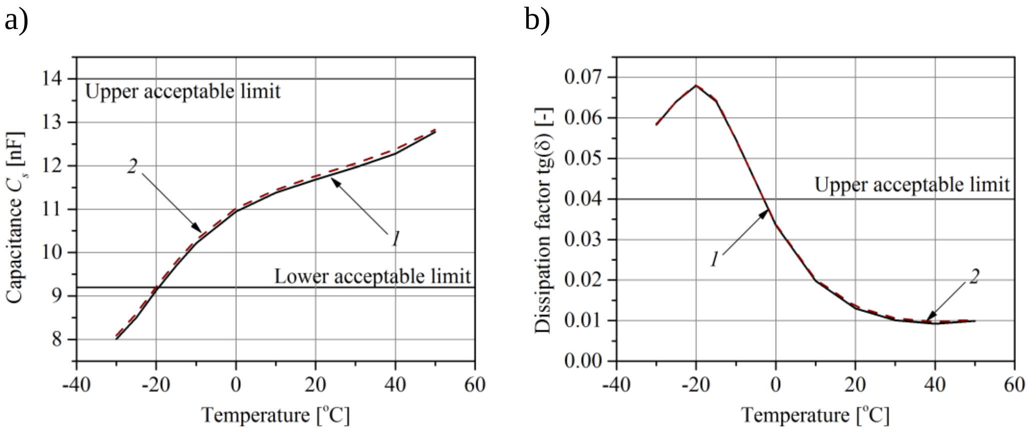

Figure 1 – The influence of temperature on: a) the equivalent capacitance of a piezoelectric polymer sensor, b) dissipation factor $tg(\delta)$, for 1-sensor with connecting cable, 2-sensor without connecting cable

$$\text{relative error} = \frac{W - W_0}{W_0} \cdot 100\% \tag{1}$$

where: W_0 - the result of processing signals from the sensor for temperature +20°C.

The plot of error (1) versus the sensor temperature is shown in Figure 2. As follows from this characteristic the temperature rise of 20°C over the reference temperature results in a weighing error of about 4%. At extremely low temperatures this error may be contained within the range 10-20%.

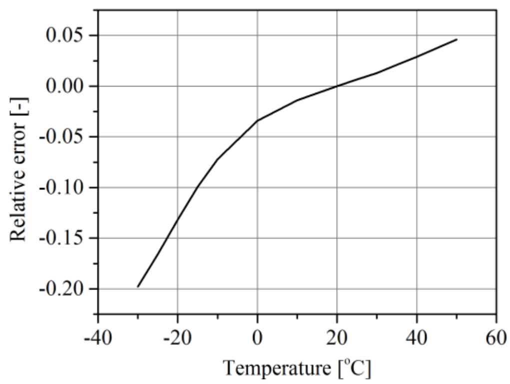

Figure 2 – The weighing error in a WIM system equipped with piezoelectric polymer sensors, arising exclusively from a change in the sensor parameters due to a change in temperature

4. Sensor external errors

Load sensors are installed in the asphalt or concrete road pavement. Regarding the method of installation, it should be presumed that the pavement mechanical properties, which depend on the temperature, could also influence the correctness of weighing. This phenomenon causes a sensor external error. Its level can only be evaluated by means of on-site experiments carried out at the WIM site. The characteristics that describe WIM system thermal properties have been determined using reference vehicles (Burnos 2008). In Poland five-axle articulated vehicles, including two-axle tractors and three-axle semi-trailers, are categorized into this class. The load of the first axle of these vehicles is most weakly correlated with loads of other axles and total mass and was chosen for reference value.

The metrological properties of WIM systems equipped with polymer (RoadTrax BL, MSI) and quartz (first generation of Lineas sensors by Kistler) axle load sensors were evaluated. Data from two WIM systems were collected for this purpose, which were located on national roads in Poland. The data were collected in different periods depending on the weighing site, but the operating time of each site was not shorter than 6 months. In total over 3 million of all types of vehicles were recorded, including cars, vans, buses, etc. of which 0.15 million records of five axle trucks were used in the analysis presented in this paper.

The analysis of the results of reference vehicles' first axle weighing consists of assessment of the error value (1) at the specified pavement temperature and for the given range of reference vehicles' speeds. Each point of characteristics shown in Figure 3 is the average value of results of weighing at least several dozen vehicles. It should be emphasized that the characteristics shown in Figure 3 take into account the temperature influence on the intrinsic properties of a sensor and on the pavement parameters, and hence the total relative error of vehicle weighing. Both WIM systems were calibrated at the temperature of 15°C.

From the characteristics shown in Figure 3 the following conclusions can be formulated:

- WIM systems employing polymer sensors are definitely more sensitive to temperature changes than quartz sensors. A temperature change within the range –20°C to +30°C may produce as an effect a change in the weighing result of approximately 50%, whereas in the case of quartz sensors that change is approximately 7%.

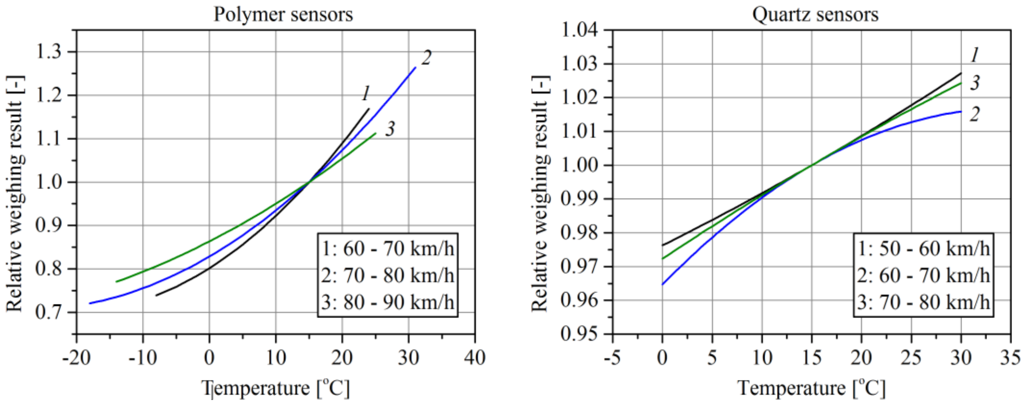

Figure 3 – Comparison of temperature characteristics of polymer and quartz sensors installed in asphalt

- In both cases of load sensors, the temperature characteristic of weighing error depends on the weighed vehicle speed. That means applying a correction for the temperature influence on the weighing result requires knowledge of the whole family of characteristics determined for various speed values, or a complete two dimensional characteristic.
- Considering daily variation of pavement temperature observed in a temperate climate, it is not possible to achieve better accuracy than 7% in a WIM system equipped with quartz sensors without temperature correction.
- Comparing characteristics determined for polymer sensors shown in Figures 2 and 3, allows to separate quantitatively two causes of the weighing results sensitivity to temperature, i.e.: the influence of the sensor intrinsic parameters change (sensor intrinsic error –12% to +2%), and the influence of the pavement parameters change (sensor external error –25% to +25%) over a temperature change range of –20°C to +30°C.
- Shape of the characteristic in Figure 3, and the same time sensitivity of weighing results to temperature changes, depends on the pavement mechanical properties and vary from site to site. Explanation of system behaviour would required take into account stiffness model of the pavement – which was not the aim of this study. This model is complex and nonlinear in nature with 3 variables: stiffness coefficient, vehicle speed and axle load. This will be the aim of further studies in cooperation with Gdansk University of Technology.

4.1 Influence of a non-uniform distribution of pavement temperature along the site on weighing results

A necessary condition for any temperature correction of weighing results is a concurrent measurement of pavement temperature. Figure 4a shows example results of daily change of pavement temperature at an MS-WIM site equipped with five temperature sensors distributed along the site, and sixteen polymer load sensors.

As can be seen from characteristics in Figure 4a, the asphalt temperature in summer season in Poland changes during a day even by 25°C. It can also be noticed that temperature distribution along the site is not uniform. The length of MS-WIM sites depends on the number of load sensors installed and may exceed 20 meters. Therefore, temperatures at different points of a site may differ significantly, chiefly due to the non-uniform insolation caused by neighbouring trees and high buildings situated along the road. The pavement temperature change and temperature non-uniformity translate directly into the weighing error. Since the experimental MS-WIM site is equipped with polymer load sensors, this influence is very strong, as shown in Figure 4b.

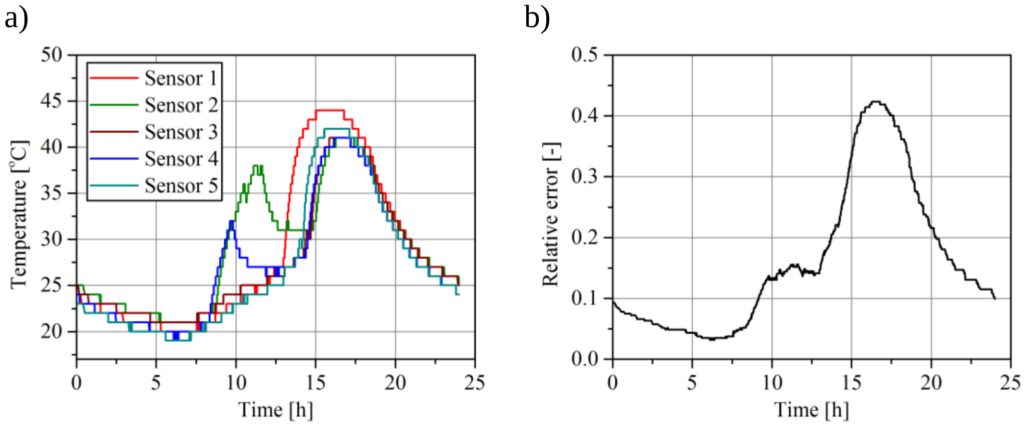

Figure 4 – a) Daily pavement temperature change at the MS-WIM site at five measurement points, distributed along the site, b) An example daily variation of the weighing error at the MS-WIM site due to the pavement temperature change

These phenomena occur typically at multi-sensor sites situated on long road sections. On WIM sites equipped with only two sensors, the distance between sensors is limited to 1m – 2m, thus effects produced by the non-uniform temperature distribution along the WIM site are much smaller.

4.2 Influence of a non-uniform distribution of pavement temperature across the site on weighing results

A non-uniform temperature distribution is observed not only along the site but also across it, i.e. along each load sensor. In this case also it may be caused by shadows cast onto the pavement by roadside objects. That means two parts of a load sensor may be exposed to different temperatures. Let's assume the situation shown in Figure 5. Two parts of the load sensor (part A and part B) are operated in different temperatures. The wheels of a given axle are rolling over both parts of the sensor and its response is a combined reaction to forces exerted by all wheels of a given axle.

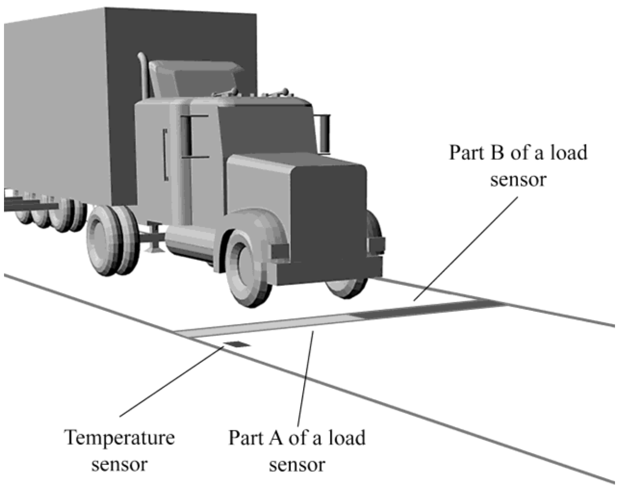

Figure 5 – A view of a two parts of load sensor

Daily changes in temperature of both parts of the load sensor, observable in the summer season, are shown in Figure 6a. Assuming the temperature sensor correctly measures the temperature of part A, and the correction of the weighing result is based on this measurement, the relative weighing error due to different temperatures of both parts of the load sensor changes during a day as shown in Figure 6b. This is one of the total weighing error components that is caused by temperature influence.

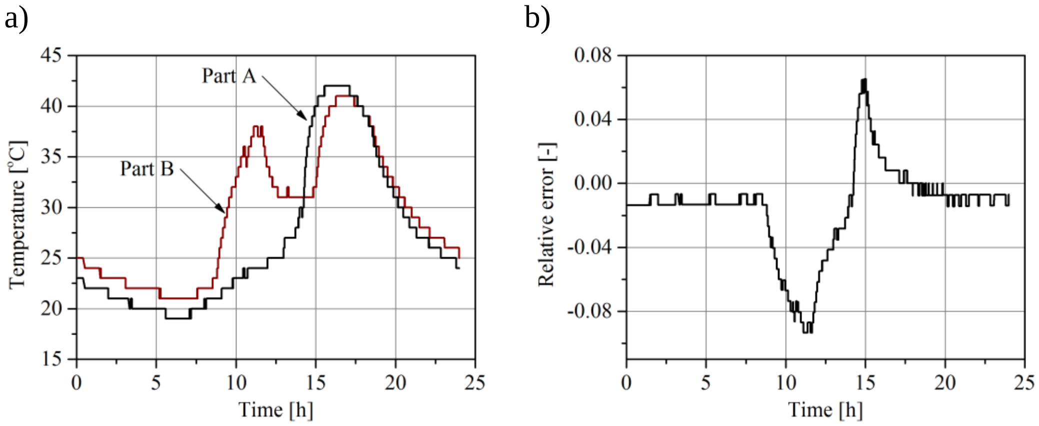

Figure 6 – An example of daily temperature variations in two parts of a load sensor: a) Part A – temperature of part A, Part B – temperature of part B, b) relative weighing error due to different temperatures of parts A and B

In such case correcting the weighing result would require the installation of several temperature sensors along the load sensor and the detection of the wheel paths of a given axle. The correction should, therefore, take into account results of temperature measurement from sensors closest to paths followed by the vehicle wheels.

5. Temperature correction of weighing results

As follows from the characteristics shown in Figure 3, a temperature change within the range of –20°C to +30°C may produce a change in the weighing result of approximately 7% for quartz sensors and of approximately 50% in the case of polymer sensors. The dependence of the weighing error on temperature can be described with good accuracy by a polynomial model (Burnos 2008). The knowledge of such a model enables online correction of weighing error but it requires continuous measuring of the road pavement temperature at a depth similar to that at which the load sensors are installed. As shown in (Gajda et al. 2013), such correction reduces the WIM system temperature error almost ten times (Figure 7a).
Nevertheless, determination of the temperature model for a given WIM site is time-consuming and costly. Thus an alternative approach can be adopted that consists of calibration of the WIM site at several selected temperatures, distributed uniformly over the range of temperature changes typical for the WIM system location.
Figure 7b shows the WIM system errors after temperature correction based on the calibration results for five temperature values (-10°C, 0°C, +10°C, +20°C and +30°C). As seen from the figure, the five-point calibration yields slightly better results than the correction based on a polynomial model. Additionally, this method from the practical point of view is much easier.

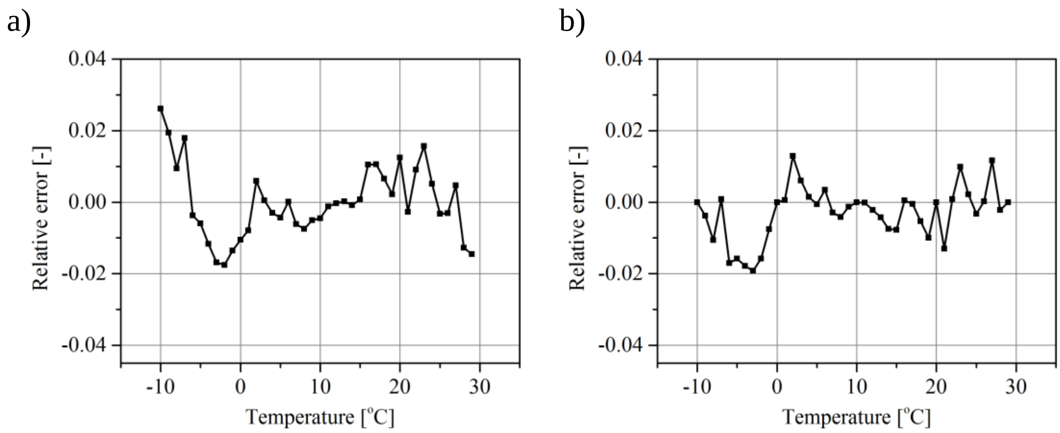

Figure 7 – a) The relative error of weighing in the WIM system after correction based on a polynomial model, b) The relative error of weighing in the WIM system after correction based on calibration for five temperature values

The temperature error has not been, however, entirely eliminated because of the limited accuracy of the polynomial model, on the one hand, and the non-uniform temperature distribution along the WIM site, on the other. Taking into account the second effect requires placing at least several temperature sensors along the weighing site. Correction of weighing results, based on the multi-point temperature measurement, enables a further reduction of weighing error. The best results were obtained when the results of temperature measurement from each sensor were separately used for correction. The worst effect was produced by correction based on the average temperature value (this method is similar to that based on the temperature measurement made at a single point).

6. Conclusions

Achieving a high and known accuracy of WIM systems would enable their use for direct enforcement purposes. Due to the influence of numerous factors limiting this accuracy, this is not an easy task. In the authors' opinion, the pavement temperature is one of significant influencing factors, moreover its value varies over a wide range in relatively short time-intervals. This phenomenon concerns both the polymer and quartz load sensors. The results presented show clearly that in the case of Lineas load sensors manufactured by Kistler, their temperature sensitivity, after installation in pavement, is about 7% within the temperature range –20°C to +30°C. It is therefore necessary to reconsider views about the method of WIM system calibration and assessing their accuracy using the pre-weighed vehicle method proposed in COST 323 (Jacob et al. 2002). Accurate Multi-Sensor WIM systems intended for mass enforcement should be calibrated and tested over a wide range of temperature change similarly as they are tested over a wide range of pre-weighed vehicles' speeds. The weighing results correction should be carried out using a two-dimensional model taking into account the vehicle speed and temperature at which the measurement was performed. Furthermore, as a result of model and laboratory research and on-site experiments, it has been demonstrated that in order to achieve a high accuracy level the WIM site should be equipped with a multi-point temperature measuring system.

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Session 2 : Use of WIM Data for Highway Traffic Monitoring and ITS

Chair: Lily Poulikakos & Martin Ruesch
(EMPA & RAPP, Switzerland)

RELATING IMPACT OF HEAVY VEHICLES TO THE EXTERNAL COSTS




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Abstract
Switzerland has been a member of the European cooperative project Eureka Logchain Footprint and its follow up Ecovehicle since 2004. The project has been successful in developing methods to identify environmentally friendly vehicles for road and rail transport modes. The footprint of vehicles was defined as dynamic load, noise, gaseous emissions and vibrations. It was shown that there was no systematic dependence of the noise emissions on the Euro emissions classes for each Swiss 10 category. This shows that the Euro-V emissions classes are not necessarily less noisy and new instruments have to be developed in order to encourage vehicles with a low noise footprint. Heavy duty vehicles were evaluated using a holistic approach taking into account a combination of all their individual footprints. The external cost of road vehicles are calculated using WIM, Noise and pollutants as contributing parameters showing how they can vary widely within the vehicle categories and impact type and a great potential to improve vehicle external costs in every category.

Keywords: Transport Footprint, WIM, Noise, Pollutants, External Costs, Weigh-in-Motion.

Résumé
La Suisse est un membre du projet européen de coopération Eureka Logchain Footprint et de son suivi Ecovehicle depuis 2004. Le projet a réussi à développer des méthodes pour identifier les véhicules respectueux de l'environnement pour les modes de transport routier et ferroviaire. L'empreinte des véhicules a été définie comme charge dynamique, le bruit, les émissions gazeuses et les vibrations. Il a été démontré qu'il n'y avait pas de dépendance systématique des émissions sonores sur les classes d'émissions Euro pour chaque catégorie suisse 10. Cela montre que les classes d'émissions Euro-V ne sont pas nécessairement moins bruyants et de nouveaux instruments doivent être développés afin d'encourager les véhicules à faible empreinte sonore. Les véhicules lourds ont été évalués en utilisant une approche globale prenant en compte une combinaison de toutes leurs empreintes individuelles. Le coût externe des véhicules routiers sont calculés en utilisant WIM, le bruit et les polluants comme paramètres qui contribuent montrant comment ils peuvent varier considérablement que ce soient les catégories de véhicules et le type d'impact et un grand potentiel pour améliorer les coûts externes des véhicules dans chaque catégorie.
Mots-clés: Footprint de transport, WIM, bruit, émissions gazeuses, coûts externes.

1. Introduction

Greater demands on the road transport infrastructure as a result of economic growth have manifested themselves in an increase in the number of Heavy Duty Vehicles (HDV) worldwide. This increase is inherently accompanied by increase in congestion, noise, energy use and pollutant emissions as well as an increase in the infrastructure overuse. Although noise and infrastructure costs are primarily local effects, the increase in transport induced greenhouse gases (GHG) is a global problem contributing significantly to climate change and must be dealt with globally. To this end, comprehensive instruments are needed in order to encourage vehicles with a low environmental footprint.

Switzerland has been a member of the European cooperative project Eureka Logchain Footprint and its follow up Ecovehicle since 2004. The results of the measurements made show that in almost every vehicle category there are those with a very high combined footprint.
A recent study by the Swiss federal office for spatial development calculates the external and social (national economic) environmental, accident and health-related effects of transport in Switzerland in 2010. In this paper using such data the external cost of road HDV are calculated using measured WIM, Noise and pollutants as contributing parameters.

2. European Cooperative Project Ecovehicle

Switzerland has been a member of the European cooperative project Eureka Logchain Footprint since 2004. The project has been successful in developing methods to identify environmentally friendly vehicles for road and rail transport modes (www.eureka.be, Mayer et al., 2012; Morgan, Poulikakos, Arraigada, Partl, & Muff, 2008; Poulikakos, Heutschi, Arraigada, Anderegg, & Soltic, 2010; Poulikakos, Heutschi, & Soltic, 2013; Poulikakos, Lees, Heutschi, & Anderegg, 2009; Poulikakos et al., 2008). The footprint of vehicles was defined as dynamic load, noise, gaseous emissions and vibrations. The contributions of the Swiss partners have been in three phases. In phase I; a footprint monitoring site was installed in order to measure the footprint of passing vehicles using innovative techniques. In phase II it was shown that parameters that are currently controlled and their reduction encouraged such as gaseous emissions, axle loads and gross weight are for the most part below or close to acceptable limits. However other important parameters such as tire pressure and noise remain to be higher than acceptable limits. In Phase III it was shown that there was no systematic dependence of the noise emissions on the Euro emissions classes for each Swiss 10 (Tab. 1) category (Figure 1).

Tab. 1 Swiss 10 vehicle categories

Swiss 1	Buses
Swiss 5	Delivery truck
Swiss 6	Delivery truck with trailer
Swiss 7	Articulated delivery truck
Swiss 8	Freight truck
Swiss 9	Freight truck with trailer
Swiss 10	Articulated freight truck

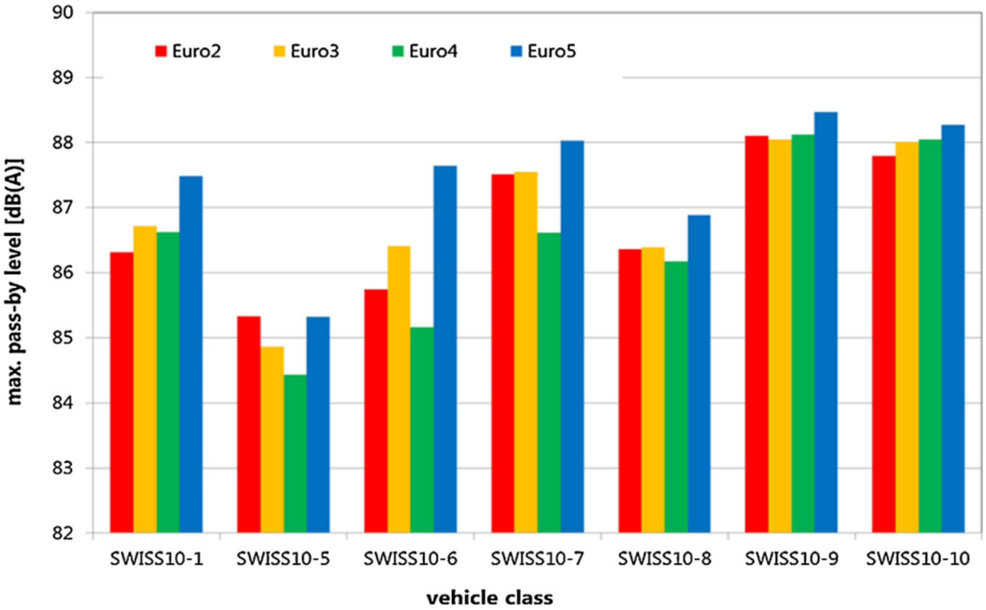

Figure 1-Maximum sound pressure level, SPL for each Swiss 10 vehicle category and Euro emissions category (Poulikakos et al., 2013)

Figure 1 shows the measured by pass noise emissions at the Swiss monitoring site between Zurich and Bern per vehicle category and euro emissions category, showing that the newest engines with Euro V emissions classes are not necessarily less noisy. It was concluded that new instruments have to be developed in order to encourage vehicles with a low noise footprint. In addition a noise emissions model was developed, allowing the individual footprint of a vehicle to be estimated from parameters that are known or observable. Furthermore, 2 Models were proposed for the calculation of the total footprint of heavy vehicles (Poulikakos et al., 2013). This total footprint model was based on combining non-dimensionalised values for euro emissions category, axle load or gross mass and noise. With the help of the total footprint models developed, heavy duty vehicles could be evaluated using a holistic approach taking into account a combination of all their individual footprints. The results show that in almost every category there are vehicles with a very high combined footprint, showing the potential for reducing this footprint (Figure 2).

The current differential charging scheme based on Euro emissions classes (discussed in the next section) successfully implemented by the Swiss Heavy Vehicle Fee (LSVA) will not be effective in the longer term in encouraging vehicles with a low total environmental footprint as the updated vehicle fleet is mostly Euro V which was shown is not necessarily less noisy (Figure 1). Furthermore, noise from road traffic incur significant external costs, these costs could be recovered by the Heavy vehicle fee, but – since noise is not a criteria in the charging scheme - there is no incentive to purchase less noisy vehicles.
The European cooperative Eureka Ecovehicle (E! 7219) project is a follow up to footprint (E!2486) with the following global aims:

- to develop an environmental label for road and rail vehicles
- to relate impacts to costs for individual vehicles

The project has received Eureka label E!7219 in 2014 which is necessary to get funding in some countries. The current members of the project are Switzerland (Empa, Quantis, Kistler); Czech Republic (SVUM), United Kingdom (Sciotech Projects, q-free).

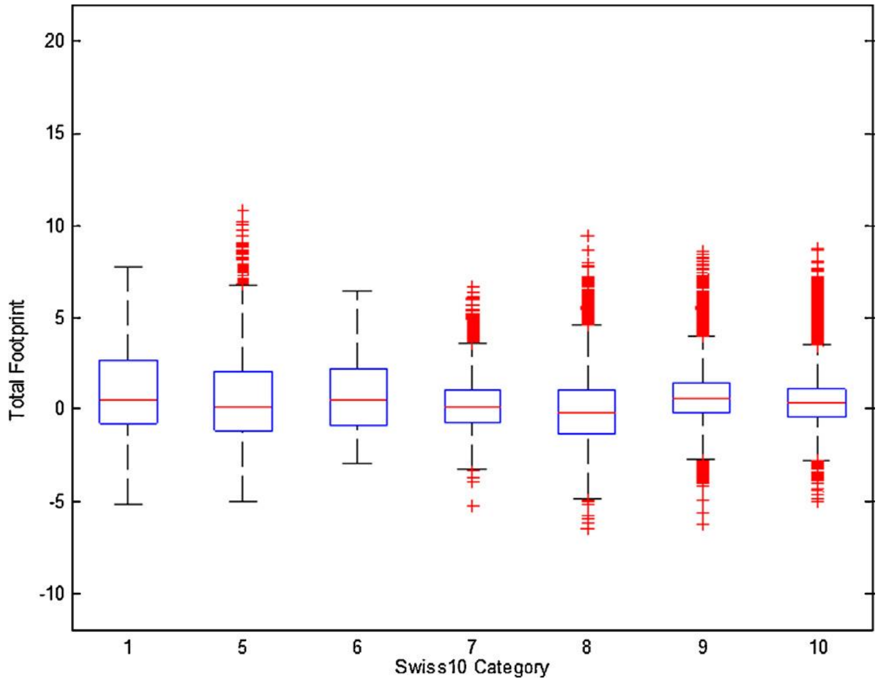

Figure 2- Box plot showing distribution of total footprint based on euro engine category, noise and axle load, of Swiss 10 vehicle categories (Table 1). (Poulikakos et al., 2013)

3. External Cost of Transport

The Swiss Heavy vehicle Fee (LSVA) is a differential charging scheme that applies to HGV over 3.5 t and is calculated based on three criteria:

- Number of kilometers travelled in Switzerland
- Allowable gross vehicle weight of the vehicle
- The gaseous emissions of the vehicle based on the vehicle engine type approval record

The purpose of the fee is to recover some of the external costs of transport. Internal costs are those that are covered by the user for example paying for gas or buying a train ticket. External costs are those that are not paid by the user such as noise, accidents and pollution costs resulting from transport. According to a recent published study in Switzerland the external costs are only partially recovered by the fee (Ecoplan, Infras, 2014). The current rate for the LSVA is shown in Tab. 2 and indicates that there is a bonus for particle filter as well as Euro VI engines which are the cleanest on the market today.

The external costs of transport due to air pollution (health) and noise are as listed in Tab. 3. These are two parameters that are used in the Ecovehicle project and therefore singled out here. As shown the external costs of freight trucks and articulated trucks with semi-trailers are similar per driven kilometer. However when the tonnage is also considered the costs of semi's are lower since they can transport more tonnage.

Tab. 2- Current heavy vehicle fee and bonus/Malus rate in Switzerland (http://www.ezv.admin.ch/zollinfo_firmen/04020/04204/04208/04744/index.html?lang=de, accessed 8.1.2015)

		CH Ct/t-km	% bonus/ malus	Euro II,III with part filt CH Ct/t-km	% bonus/ malus
Cat 1	Euro 0,I,II	3.1	15.2	2.8	-3.7
Cat 2	Euro III	2.69		2.4	-10
Cat 3	Euro IV+	2.28	-15.2		
	Euro VI	2.05	-23.8		

According to the external cost report (Ecoplan, Infras, 2014), the infrastructure damage costs were calculated to be 400 Mio CHF. According to the data from the Swiss tolling office the transport performance was 69 Bio tkm in 2014. Therefore the external cost of infrastructure damage can be calculated to be 0.58 Rp/tkm.

Tab. 3- External Costs of heavy vehicles due to air pollution and noise (Ecoplan, Infras , 2014) (Rp=Swiss cents)

External cost	Rp/km	Rp/tkm	Rp/km	Rp/tkm
	air pollution		noise	
Li (Delivery Trucks; Cat 5,6,7)	3.6	12.4	3.8	13
LW (Trucks, Cat 8, 9)	11.7	2.2	15	2.9
SS (Articulated Vehicles, Cat 10)	11.1	1.1	15	1.4

4. Relating Impacts to Costs

The data used for the calculations presented in this paper were obtained from the WIM and LSVA monitoring site at Oberbuchsiten between Zurich and Bern in Switzerland, that was combined with a microphone for the noise measurements as explained in detail elsewhere (Poulikakos et al., 2013). The data was obtained in March, September and November 2011. 350’000 vehicles were analyzed after going through a data reduction procedure to ensure valid measurements.

In order to calculate the costs associated with the impacts, it was assumed that the external costs reported in Tab. 3 were for average vehicles. In order to determine the external costs per impact category the cost was related to how far the impact was from the impact of an average vehicle for that category and impact type.

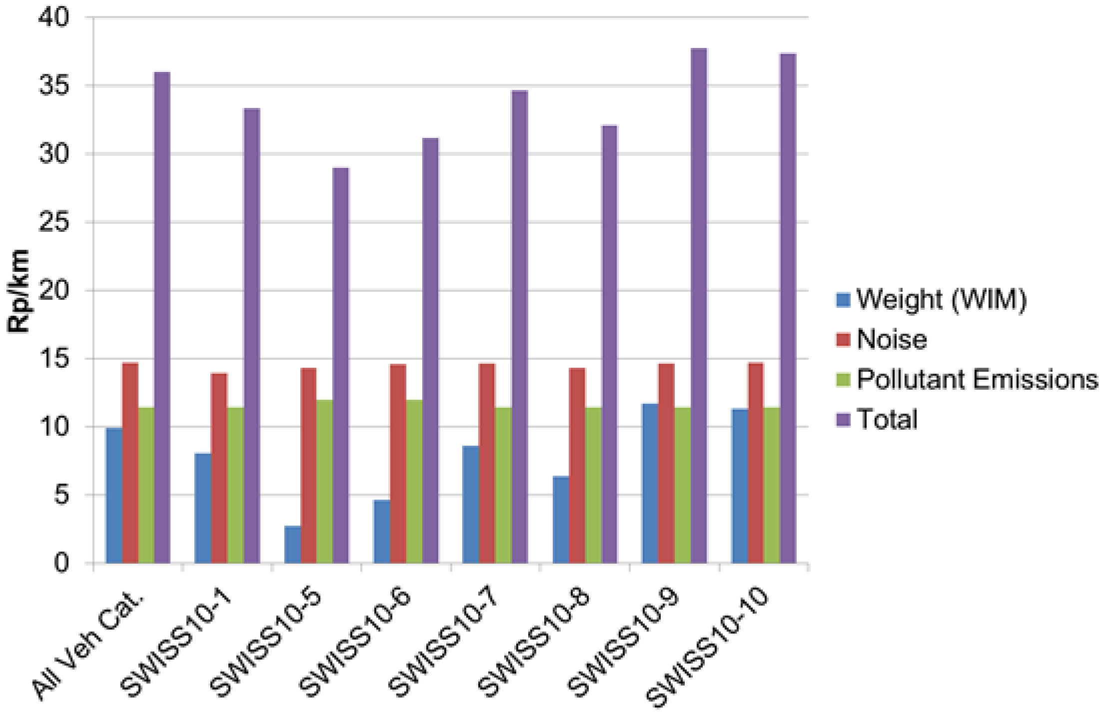

Figure 3- Median of external costs of noise, load and pollutants per verhicle category (Rp=Swiss cents)

Figure 3 shows the median cost for infrastructure damage (proportional to weight measured by WIM sensors), pollutants (proportional to Euro category) and noise (proportional to pass by measurements). As shown in Figure 3, the external costs of heavy vehicles can vary widely within the vehicle categories and impact type. The median costs for pollutants between the vehicle categories are similar as most vehicles are now Euro V. As discussed previously, the current Swiss heavy vehicle fee encourages low polluting vehicles but no provisions are made for low noise vehicles. Figure 3 shows that the median cost per vehicle of noise is higher than for pollutants. The median cost for weight carried is lower for the smaller vehicles as they carry less weight. The results show that on average the total external costs per kilometer of vehicle classed 9 and 10 are greater than the other categories.

5. Conclusions and Outlook

The results of this project show that the various environmental impacts of heavy vehicles incur costs and these costs are not equally distributed within vehicle categories and impact types. In order to encourage vehicles with a low environmental footprint it is important to identify what these impacts are and encourage the reduction of these impacts through legislation, education and incentives.

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TEST SITE FOR EVALUATION OF HIGH-SPEED WIM AND ITS SOLUTIONS IN BRAZILIAN CONDITIONS





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Abstract
The Brazilian Federal Department of Transportation Infrastructure (DNIT) and the Transportation and Logistics Laboratory at the Federal University of Santa Catarina (LabTrans / UFSC) launched a comprehensive project for the evaluation of high-speed weigh-in-motion (HS-WIM) systems in Brazilian conditions. This paper presents an assessment of aspects related to implementation, integration, and operation of HS-WIM systems and other ITS solutions for a number of desired applications in the Brazilian federal road network. Based on developments and field observations a set of recommendations are drawn for the use of WIM in Brazil.

Keywords: Intelligent Transportation Systems, ITS, Weigh-in-Motion, WIM, Brazil.

Resumo
O Departamento Nacional de Infraestrutura de Transportes (DNIT) e o Laboratório de Transportes e Logística da Universidade Federal de Santa Catarina (LabTrans/UFSC) lançaram um abrangente projeto para a avaliação de sistemas de pesagem em movimento em alta velocidade (HS-WIM) em condições brasileiras. Este trabalho apresenta a avaliação de aspectos relacionados à implantação, integração e operação de sistemas HS-WIM e outras soluções de ITS para diferentes aplicações na malha rodoviária federal brasileira. Baseado em desenvolvimentos e observações de campo, uma serie de recomendações são elencadas para a utilização de sistemas WIM no Brasil.

Palavras-chave: Sistemas Inteligentes de Transportes, ITS, Pesagem em Movimento, WIM.

1. Introduction:

The increasing volume of heavy vehicle traffic and the limitations in human resources have motivated the Brazilian federal government to promote developments that gradually allow for higher levels of automation in weight enforcement and traffic data collection processes adopted in the Brazil. In this context, several efforts have been carried on by DNIT and LabTrans/UFSC in order to support the implementation of WIM in the country.

In the end of 2013 a research project was launched for the evaluation of HS-WIM in integration with other ITS technologies. For this project, a test site was built over a 200 meter stretch of road BR-101 SB, in the municipality of Araranguá, Brazil. The developments and evaluations in context of the project were also performed with a legacy test-site implemented in 2009 for studies on multiple-sensor WIM and situated in the same area.

This project takes into consideration the following potential applications of WIM in Brazilian conditions:

- Traffic data collection
- Pre-selection for overloading enforcement
- Company Profiling.

International experience shows that different local conditions, such as pavement structure, climate, traffic and vehicle fleet, may influence in the overall performance of WIM systems. Hence, one of the objectives of the project is to provide an assessment of the performance of WIM systems in terms of measurements, durability and consistency of operation. The second goal of the project is to evaluate the performance and feasibility of WIM systems in integration with different ITS solutions for applications in overload control.

2. Test-site Layout

Figure 1 presents the layout of the test-site built specifically for the project, where the implementation of two complete HS-WIM systems and related ITS solutions took place:

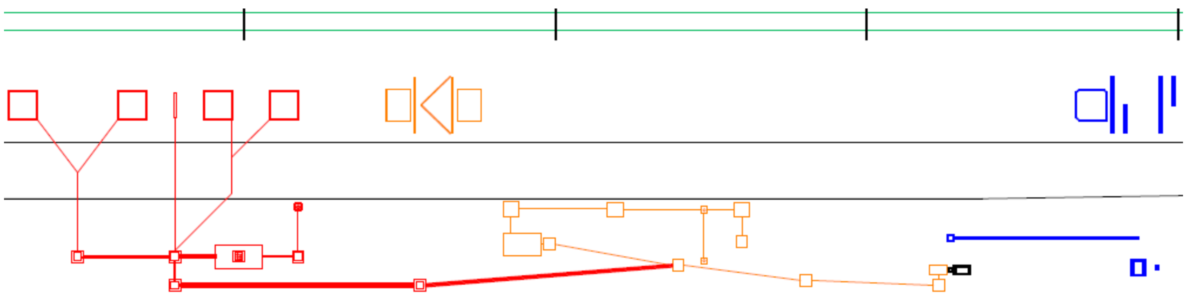

Figure 1 – BR-101 test-site layout

The drawing shows the implementation of three complete technology solutions from different suppliers, as described in the list below:

- **Blue:** Intercomp – HS-WIM.
- **Orange:** Sterela/Egis – HS-WIM and Automatic License Plate Reader (ALPR).
- **Red:** IIS – Vehicle Waveform Identification (VWI), ALPR and automatic code reader for the National Registry of Freight Motor Carriers (RNTRC).

2.1 WIM systems

Two WIM solutions were deployed specifically for the project. The first is composed by strain gauge based strip sensors manufactured and supplied by Intercomp. The second is composed by piezo-quartz sensors manufactured by Kistler and supplied by Sterela/Egis.

Another set of WIM sensors were used in the context of the project. These were previously installed for a multiple sensor experiment, and include the following sensor technologies:

- Piezo-quartz, supplied by Kistler.
- Piezo-ceramic, supplied by Electronique Controle Mesure.
- Piezo-polymer, supplied by Measurement Specialties.
- Fiber optic, supplied by Measurement Specialties.

This WIM site is built in parallel with the BR-101 road, and was originally implemented in 2009. The installation can be visualized on Figure 2.

Figure 2 – LabTrans MS-WIM test site

2.2 ITS solutions

The integration of WIM with other ITS solutions is essential for all applications envisioned for supporting overload control in the Brazilian federal road network. Thus, the project included the integration of WIM with the following technologies:

- Automatic license plate reader (ALPR)
- Vehicle waveform identification (VWI)
- Automatic RNTRC code reader.

Currently, ALPR cameras provide the only universal source for automatic vehicle identification in Brazil, and therefore are essential for both weigh station pre-selection and company profiling applications. At weigh stations, HS-WIM systems require ALPR for automatic escape detection in cases where potentially overloaded vehicles refuse to enter the enforcement site. For company profiling, ALPR allows the identification of the carrier and subsequent actions for overloading control.

The RNTRC code reader was installed with the objective of testing a different source of vehicle identification, given the importance of this function in the envisioned processes for overloading control. However, currently the RNTRC code does not cover the entire heavy vehicle fleet as it has been only implemented in commercial vehicles.

Finally, the VWI systems provide a means for vehicle identification and recognition besides the automatic license plate readers. For instance, in an automatic weigh station program such as the recently launched Automated and Integrated Enforcement Stations (PIAFs), vehicles need to be recognized in two situations:

- Matching pre-selection records with enforcement records for calibration assessment
- Matching pre-selection records with vehicle records for escape detection.

Both functions were implemented and tested in the context of the test track.

2.3 Enforcement Weigh Station

In order to evaluate the application of the HS-WIM test site for pre-selection of potentially overloaded heavy vehicles, two extra data collection points were installed at DNIT 1608 fixed weigh station, located about 2,000 meters downstream traffic in the same road. These data collection sites are equipped with VWI sensors and overview cameras, which allow for the recognition of vehicles in different points of the enforcement station after they run through the HS-WIM test-site. Figure 3 shows, in red, the installation layout of these systems within the enforcement station area.

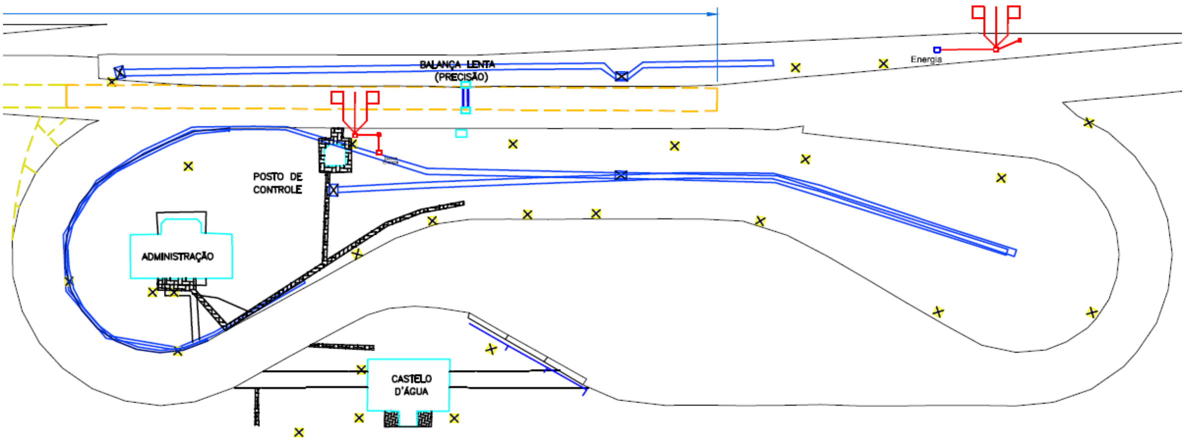

Figure 3 – VWI implementation at 1608 enforcement weigh station

In addition to allowing the assessment of HS-WIM as a pre-selection tool in automated weigh stations, the installation of the VWIs provide a reliable way for matching the high-speed WIM measurements with the low-speed precision measurements performed inside the enforecement station, thus alowing the comparision and constant performance evaluation of the HS-WIM systems. Antennas for wireless communication provide the communication between the 3 data collection points.

3. Project Execution

The stages for the execution of the project include:

- Implementation.
- Development and integration.
- Performance assessment.

3.1 Implementation

For the purpose of the project and the installation of WIM sensors, DNIT and LabTrans/UFSC designed and implemented a specific road stretch with approximately 200 meters of pavement, built with more robust capabilities than conventional asphalt pavements on the Brazilian federal highway network. Previous experience with WIM in Brazil shows a high probability of early deterioration of pavement and grouting around sensors installed on conventional asphalt pavements. Thus, a specially designed road stretch was implemented for testing and potential replication. The intervention for the construction works were done simultaneously with another construction project taking place on the same road. This simultaneous intervention provided with savings in resources, which can be possibly replicated in future WIM projects in Brazil.

Figure 4 shows a comparison between the new structure designed specifically for the project and the existing structure of the same highway:

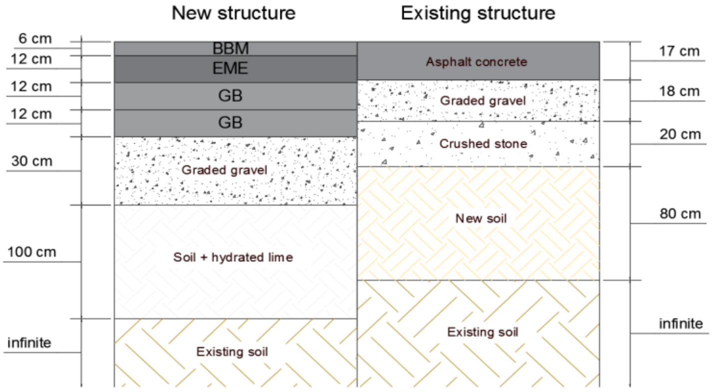

Figure 4 – Comparission of new and existing pavement structures

While the original pavement was designed according to DNIT's pavements manual (DNIT, 2006), the new pavement considers the French manual for pavement formulations (LCPC, 2007) and aims to provide an adequate structure for the installation of WIM sensors. The end result seen on Figure 4 shows a significant difference in the asphalt layers and overall depth of the structures.

For the implementation of WIM systems and other ITS solutions, conventional methods were evaluated and implemented in local conditions for cost reduction and ease of replication. Figure 5 shows the final result of the new WIM installations, with the Intercomp system (on the left) and the Sterela/Egis system (on the right).

Figure 5 – WIM installation

3.2 Development and integration processes

The aspects related to development and integration within the project included the following activities:

- Development of a HS-WIM system with existing sensor installations and locally available components.
- Development of vehicle classification system for the Brazilian heavy vehicle class scheme.
- Integration of WIM with other ITS systems.

3.2.1 *HS-WIM system development*

LabTrans/UFSC developed its own HS-WIM system with the objective of providing a reproducible methodology, which can be implemented with the use of existing sensor technologies and components available in the local market. In its core the development of the weighing algorithm started with a manual provided by the WIM sensor manufacturer Kistler (Kistler, 2004).

In this system, signal acquisition is made by two acquisition boards controlled by a local server. Quartz sensors are connected to a charge amplifier and fiber-optic sensors have a signal transducer. Ceramic and polymer sensors are connected directly to the acquisition board. After applying the filter to the signals, the algorithm implemented calculates the weight for each sensor and uses the mode to purge outlier measurements. An example of collected and filtered signals piezo-ceramic sensors is shown in Figure 6.

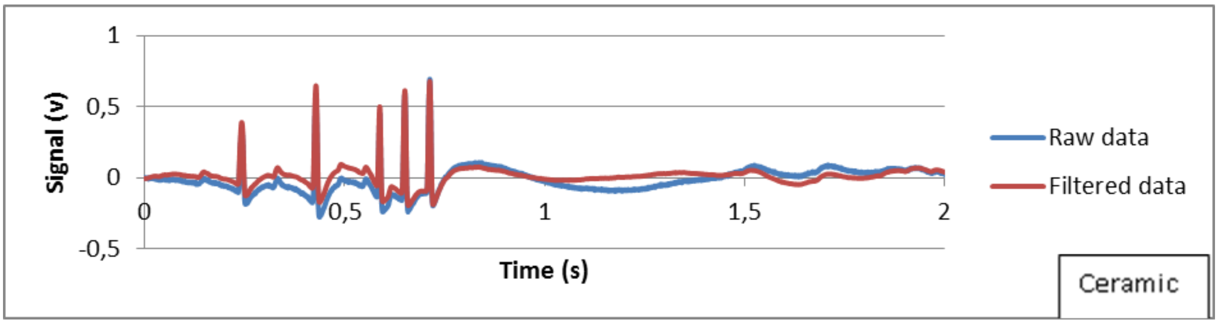

Figure 6 – Sensors raw data comparison to filtered data

3.2.2 *Vehicle classification system development*

The heavy vehicle class division used for weigh enforcement in Brazil includes over 120 different heavy vehicles classes, with class-related load limits (DNIT, 2012). The class division is based on the axle distances, axle type and vehicle length. The development and evaluation of vehicle classification systems have been carried by partner companies with the support of LabTrans/UFSC.

Currently, classification has been implemented on a limited basis, where groups of classes are assigned for each vehicle run. A full classification system will be implemented in partnership with the development team at Sterela/Egis, with the inclusion of dual tire detection as a variable for dividing the groups of classes and assigning one specific class for each vehicle run. This variable is already detected with the use two strips of piezo-polymer sensors angled at a specific degree. The identification of all truck classes is necessary as each specific class has its own specific overloading penalty criteria.

3.2.3 *Integration of WIM with other ITS systems*

The integration of WIM with related ITS solution was performed at different levels in order to allow a full assessment of the use of WIM for different applications within the project. As a final step for the integration processes, the platform Smart Roadside Inspection System (SRIS) was implemented in order to provide a full integration of the systems and the respective data collected. Figure 7 shows the user interface provided by SRIS, emulating a fixed weigh station application with the integration of WIM and vehicle identification systems:

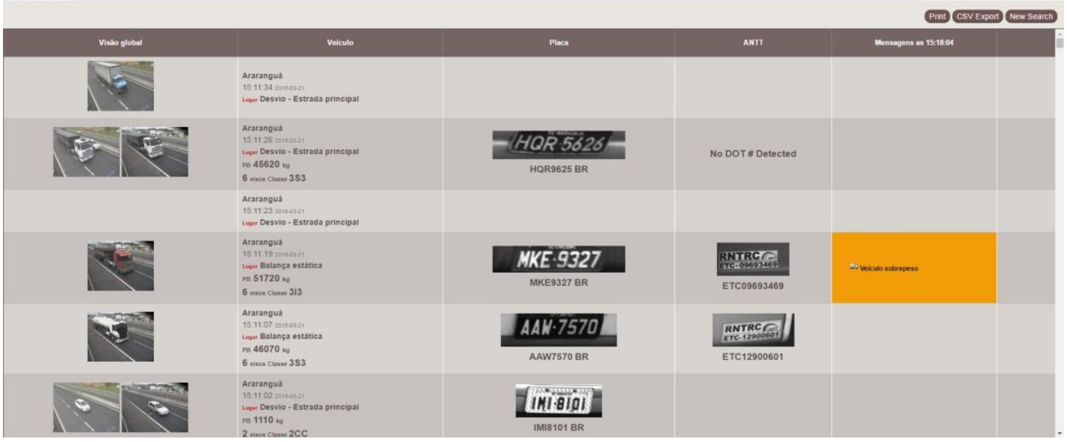

Figure 7 – SRIS integration platform

3.3 Performance assessment:

The performance assessments in the context of the project are done for the following individual aspects:

- Physical conditions of installations.
- HS-WIM measurements.
- Vehicle classification.
- Vehicle identification by ALPR and RNTRC code reader.
- Vehicle recognition by VWI systems.

The physical and operational conditions of the installations remained stable throughout the execution of the project, with the exception of the WIM systems installed over regular pavement on the legacy MS-WIM site. Figure 8 shows an example of deterioration of the WIM installations on the legacy MS-WIM test-site

Figure 8 – Pavement deterioration of MS-WIM site

The assessments of HS-WIM measurements were based on methods and recommendations present on COST 323 (2002). The evaluations were performed with the aid of a LS-WIM enforcement system, which was has been used as a reference for the evaluation of the high-speed measurements. Table 1 summarizes the results with the strain gauge and piezo-quartz HS-WIM systems implemented on the BR-101 highway:

Table 2 – Performance of WIM systems

WIM result	Test conditions	Period (after calibration)
A(5)	R1 (I)	1-2 months
B+ (7)	R1 (I)	2-3 months
B(10)	R2 (II)	12 months

The strain gauge and piezo-quartz HS-WIM solutions implemented on BR-101 were evaluated over 12 months for GVW measurements. Both systems presented performance A(5) in the first month and B(10) in the last month of evaluation. The first three months of operation were assessed under limited reproducibility conditions (R1) and environmental repeatability (I), and the results ranged between A(5) and B(7) in these tests. The remaining of the months included tests under full reproducibility conditions (R2) and limited environmental reproducibility (II).

Class C(15) was temporarily tested when the road surface area deteriorated around the strain gauge system but it returned to perform on class B(10) after the situation was solved. So far, the results on axle loads and axle group loads are not conclusive and further evaluation will provide a more precise assessment. This has been prevented by an incompatibility in the output format of the systems, which should be solved upon the completion of the project.

The HS-WIM solution developed by LabTrans/UFSC with the use of piezo-quartz sensors have shown compatible results with the commercial solutions in the terms of GVW measurements in the tests performed two weeks after calibration, as shown on Table 1:

Table 3 – Performance assessment of LabTrans/UFSC HS-WIM system

WIM result	Test conditions	Period (after calibration)
A(5)	R1 (I)	2 weeks
D+ (20)	R2 (II)	12 months

The system was tested on class A(5) for GVW measurements in its first assessment. Twelve months later, mostly due to poor pavement conditions over the legacy MS-WIM test site, the system's performance had deteriorated to class D+ (20).

The assessments over vehicle classification, vehicle identification and vehicle recognition performances have not yet been done individually, and it will be addressed within the start of 2017.

4. Results and recommendations

- **Implementation:** Pavement design and construction constitutes a vital process for the implementation of WIM systems in Brazilian conditions. As well, timing of the construction processes is important in order to reduce costs and minimize disruptions in the traffic flow

- **Implementation:** A more widespread adoption of WIM applications in Brazil may be achieved if the main challenges to implementation are successfully addressed: high costs for pavement works and system acquisition; large and growing number of heavy vehicle classes and respective load limits; limitations in vehicle identification due to poor plate conditions and reflectivity standards
- **Integration:** Integration among WIM and other ITS systems allows for applications such as automatic pre-selection at weigh stations and company profiling. Reliable technologies for vehicle recognition are especially important for applications of WIM in the context of automated fixed weigh stations
- **Development:** Despite the large number of heavy vehicle classes Brazil, the developments over vehicle classification based on axle configuration have shown promising results over the most representative vehicle classes. The addition of dual tire detection to the measurements of axle count and distances may provide the necessary standards for automated enforcement processes
- **Development:** Measurement performance of WIM systems in Brazilian conditions showed to be satisfactory provided the existence of an appropriate pavement structure for the installation. Systems may be developed in Brazil by the integration of existing sensor technologies with components available in the local market
- **Performance assessment**: Individual performances on vehicle classification, vehicle identification and vehicle recognition will be assessed within the conclusion of the project.

5. Conclusions

A comprehensive project was launched by LabTrans/UFSC and DNIT for the evaluation of high-speed WIM and ITS solutions in Brazilian conditions. The results of the project have been used as recommendations for the Automated and Integrated Enforcement Stations (PIAF) and the National Plan on Traffic Count (PNCT), which together will account for the implementation of over 350 WIM sites in Brazilian federal road network.

Over the course of the project, different WIM systems and sensor technologies were implemented and integrated with other ITS technologies, allowing for an assessment of different applications related to overload control. Different aspects of implementation and operation of the systems have been developed and evaluated, so recommendations could be drawn, providing subsidy for a more widespread use of WIM systems in Brazil.

The expected future results include a full assessment of the capabilities of the systems installed for each envisioned application, providing subsidy for future WIM implementation in Brazil.

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BENEFITS OF A WEIGH-IN-MOTION SOLUTION FOR TOLL COLLECTION IN BRAZIL

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Abstract

The Brazilian Federal Government published on the 2nd of March 2015 the 13.103 law, where the article 17 states that trucks without load do not have to pay toll for axels which do not touch the road.

In this paper we describe the Weigh-In-Motion solution, in short WIM, in particular how this system can collaborate with the actual federal law in Brazil for tolling trucks per axles with the latest stereoscopic sensor technology developed to achieve the most accurate axle detection in combination with WIM.

Keywords: Weigh-In-Motion, Toll collection based on loaded vehicles, Stereoscopic sensor technology for axel detection

Résumé

Le 2 mars 2015, le gouvernement fédéral brésilien a publié la loi 13.103 dont l'article 17 stipule que les camions sans charge n'ont pas à payer de péage pour les essieux qui ne touchent pas le sol.

Dans cet article, nous décrivons la solution de pesage en marche (WIM) en particulier comment ce système peut collaborer avec la loi fédérale actuelle au Brésil pour les camions de péage par essieu avec la dernière technologie stéréoscopique, qui peut fournir la détection de l'essieu le plus précis en combinaison avec WIM.

Mots-clés: Pesage en marche, Péage basé sur la charge des véhicules, technologie stéréoscopique pour la détection des essieux.

1. General Instructions - Case study

In the year 2015 after the nation trucker strike in Brazil, the Federal Government of Brazil published the law 13.103 in which its article 17 states that trucks without load do not have to pay toll for axels which do not touch the road.

The big question is, how the axles can be identified when the truck arrives to a toll plaza and if this truck has a load or not. This question is still open to be answered.

For these reason Kapsch proposed uses High-speed WIM solution to be placed on the main line of the highway in front of the tolling plaza (see figure 1).

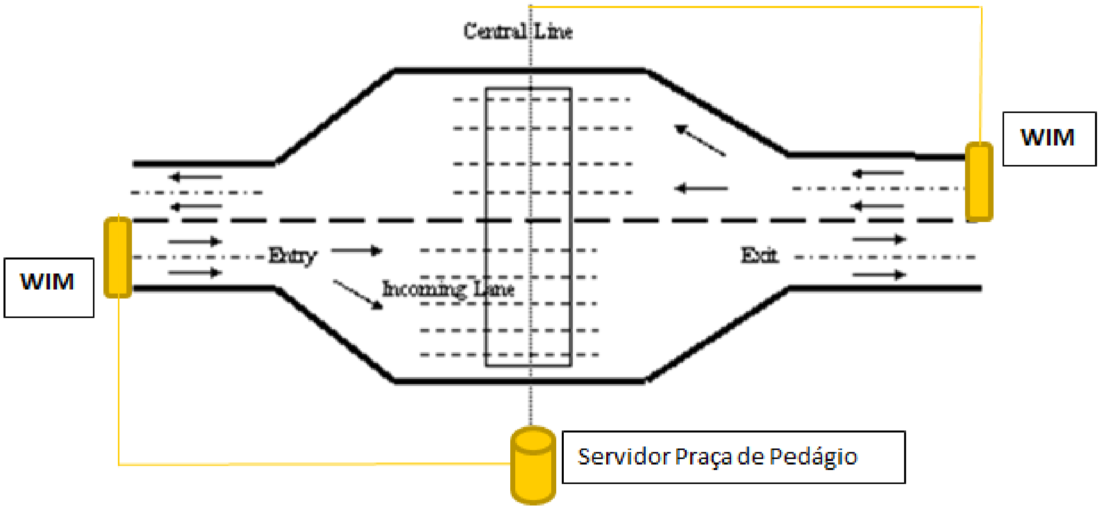


Figure 1 - High-speed WIM station before Tolling Plaza in Brazil

The main line Kapsch High-speed WIM solution will detect, identify, classify, and weight control for all vehicles passing at this place. Each transaction should be placed at the toll server plaza to be consulted for each toll booth in order to know if the truck has or not load and consequently charge these axels in the toll rate.

The main benefit of this WIM layout is that only the highway lanes has to be covered and not every lane at the tolling plaza side. This High-speed WIM setup reduces on one hand the installation and on the other hand the regular maintenance costs. Independent on any Stop & Go traffic at a tolling plaza, the High-speed WIM provides a high weight measurement accuracy and provides the weight data in real-time to the tolling plaza officer.

If the weight measurement will take place at the tolling plaza at low speed, all plaza lanes have to be equipped with scales, which requires much more construction costs, than just a WIM installation on the main highway lanes.

A time shifted operation of a centralized load control system compared to the operation of a High-speed WIM solution with real time availability of the load data from the vehicles, can occur a time delay to the tolling plaza officer. Such a time delay on the provided truck information can effect that a truck will receive a unjustified fine for a transport, which was already been delivered and unloaded.

Furthermore the High-speed WIM system at the main lines of the highway will provide the enforcement officer more time to react, also for catching e.g. a stolen car, as the information is provided in advance by matching any black-lists with the present license plate number of the vehicle already at the WIM station side before the detected stolen car arrives at the tolling plaza.

So the benefits for WIM are relevant because almost all vehicles passing the WIM station will be weighted, classified and identified before reaching the toll plaza at relevant reduced costs. The identification is done by LPNR and SINIAV RFID and the classification is done combining piezo-quartz weight sensors, laser scanner, magnetic loops and/or stereoscopic sensors. Synergies of others applications can be done without any other complementary equipment. These applications can improve further road safety by using SSE (Section Speed Enforcement), spot speed enforcement, tracking the travel of dangerous goods, monitoring of ANTT and DNIT authorization.
Furthermore with the gathered records of license plate numbers any stolen vehicles and exchanged licence plates can be detected too. The WIM system has also the possibility of interconnecting to an Electronic Tolling System also well as to a Traffic Surveillance Management system.
The integration of weight as tolling criteria indicates the deployment and the integration of WIM stations into a tolling system. So for vehicle direct enforcement in a multi-lane free-flow environment WIM provides the required information to meet the legislative requirements for direct enforcement.
In the future further WIM applications through expanded range of new features could be:

- An improved data quality for repair and maintenance of the road infrastructure and optimizing of its life cycle.
- A fully automatic Direct Enforcement of overloaded vehicles
- Functional element in PPP infrastructure projects

1.1 System functionality of the WIM solution

The Weigh-in-Motion system is developed to deliver high accurate weight information of passing free flow traffic on highways or rural roads. Therefore intelligent algorithms calculate out of the raw data stream in the Weigh-in-Motion controller signals from in road sensors to weight information. Weigh-In-Motion system is to measure several parameters of vehicles, like weight, height, speed, axles number, axles distance and to identify the vehicle using automatic number plate recognition short ANPR as well as making records of the corresponding license plate numbers. These records can be stored and evaluated via a mobile Enforcement or via Central System.

The Roadside Front-End (RFE) of the solution identifies, weighs on the mainline at highway speed via Weigh-In-Motion and ALPR technology. These technologies meet high standards of performance dictated by the European specification of WIM by COST323 and industry leading ALPR OCR performance. The measurements and data collected are collated and merged into a vehicle transaction record with gross total weights guaranteed accurate within ±5 percent according to the European specification of WIM by COST323 WIM site I (Excellent) classification and criteria.

For an advanced validation of the measured passage the system must properly detect the behavior of the vehicle and check the calibration as well as the declared class of accuracy With a WIM Validity Check System (VCS) Direct Enforcement can be enabled by showing 0 Validity flags, this means that the measurement is 100% valid and ready for the Direct Enforcement process. The system shall provide the following different validity checks displayed in the WIM GUI (see figure 3):

1. driving aside scale
2. accelerating
3. decelerating
4. non-uniform driving
5. chassis vibration
6. speed below limit
7. speed above limit
8. gross weight out of range
9. axle weight out of range
10. partially out of sensors
11. vehicle between lanes
12. measure half vehicle weight
13. vehicle not weighed
14. vehicle is unevenly loaded
15. calibration mode

Figure 2 Validity Check System GUI

Considering the Direct Enforcement purpose of the Kapsch WIM solution its main configuration consists of the following layout based on three rows of WIM piezo-quartz sensors:

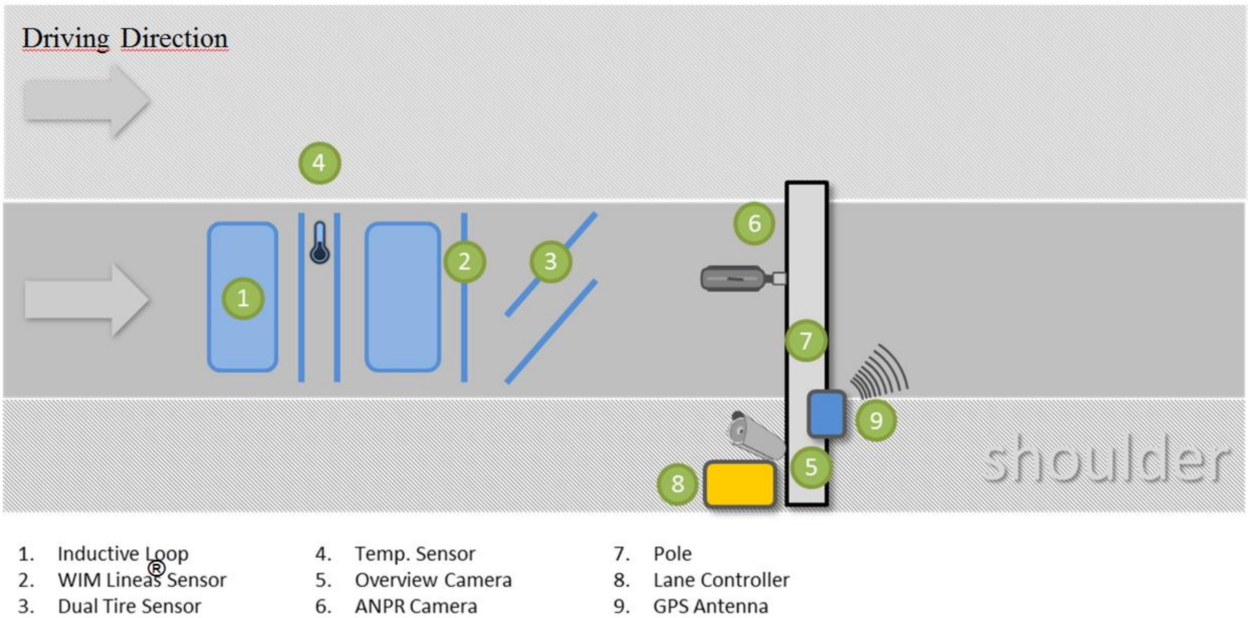


Figure 3 - Main configuration of the WIM system

2. How Direct Enforcement works for WIM and Tolling

Figure 4 - WIM Direct Enforcement System Concept

A real world example of modern weight enforcement is Kapsch's WIM pilot Direct Enforcement project in the Czech Republic. This pilot project, in conjunction with a truck tolling system, is conducting weight enforcement services directly off WIM readings using Kapsch's state-of-the-art technology. Working in collaboration with customs and police agencies, Kapsch is able to reduce the number of over-weight vehicles on a roadway while ensuring each vehicle is properly tolled.

In the USA, this solution also addresses the on-going federal concern of whether states are investing sufficient effort in weighing trucks to lengthen the service life of United States' roads and bridges.

In France, Kapsch is also participating on a direct enforcement of overloads research project. This research project has the aim to demonstrate the feasibility of direct overload enforcement with adapted existing WIM technologies to be certified carried out by IFSTTAR and Cerema, supported by the French Ministry of Transports (DGITM).

Vehicle records are assessed for compliance utilizing pre-established business rules established by the client state, province, region or country and define the allowable weight and other compliance focus. A compliance determination is made based on these business rules and a notification is forwarded on to the appropriate enforcement agency for appropriate intervention should a violation be determined.

The automation of a process in which vehicles no longer need to be weighed statically induces significant efficiencies in to the system and generates significant benefits including:

- revenue from overweight fines and fees; if executed
- Increased carrier compliance and improved safety;
- roadway maintenance savings; and
- Roadway lifecycle extensions.

Automated enforcement of non-safety issues frees enforcement resources from paperwork violations to focus on safety and security while generating increased revenue for the state.

3. Description of the tolling regime for Brazil

On the 14th of October 2015, the ANTT published Resolution 4898 which describes some operational action to identify whether commercial vehicles are with or without load. One of these alternatives is to detect the gross weight for all commercial vehicles. Kapsch proposes to use the WIM concept introduced by the DNIT into the PIAF project (Estação de Controle em Pista) before each toll plaza to identify whether trucks are with or without load. The integration of WIM into a toll collection system is very simple and must be done to permit the toll collector to receive this relevant information. In the Czech Republic, Kapsch has already successfully tested the implementation of WIM into the existing tolling solution.
Traditional toll collection in Brazil uses manual lanes and ETC for dedicated lanes. Commercial vehicles in Brazil represent in some toll plazas about 40% of the traffic. Inexistent or inefficient control of weight permits to commercial vehicles be overload.
Number of axels are used in Brazil to pay toll but in Federal Highways after the 13.103 Law all numbers of axels were considered to calculate the toll prices independently if axels are or not touching the road. After the 13.103 Law toll operators do not have any tools to identified if trucks have or not weight and for these reasons axels that not touch the roads are not paying with loose of revenues. In the same law increases the tolerance to gross weight passing from 7,5% to 10%. All concessionaries in their business plan considered all commercial vehicle configurations. For these reason the ANTT (National Terrestrial Transport Agency) must compensate for loosing revenues. The problem changes the side and cur it is placed to the Agency as it has not a real-working instrument to have an accurate information how a truck is loaded or not.
For these reasons and for the big opportunity of synergies with other application using the same infrastructure, this Kapsch WIM could be a very good solution to solve this problem and to provide added value for roadway operators.

4. How to detect the lift of axles and how this affects the tolling regime

The latest technologies to achieve axle detection in a multilane free flow environment is based on a stereoscopic sensor that now has the ability to not only classify from volumetric measurements but also detect the number of axles, all with the same overhead mounted sensor. The innovation is to use a combination of 3D measurements and advanced image analysis algorithms to detect the axles. With the new version of Kapsch stereoscopic sensor a lower mounting position and a wider field of view means that the wheels of the vehicles will be visible for the cameras. When two or more sensors are used at the same time at least one sensor will have a view of the wheels while another has a full view of the vehicle. This way it is possible to calculate exactly where the wheels should be visible and the image analysis process that detects wheels (axles) will be performed at the right location for highest accuracy. The image analysis compares the wheel area with templates of wheels from other defined vehicles. The templates will adapt depending on the dimensions and features of the vehicle to compare it with similar vehicles. Also sunlight conditions, shadows and other weather conditions are taken into account when choosing wheel templates. There are also "non-wheel-templates" available that detects parts similar to wheels to avoid false positives. The matching is done for all exposures during a passage meaning that a wheel will get input from several locations to reduce potentially noisy behaviour in individual exposures. The individual centre point for each wheel is located and this information makes it possible to detect if certain axles are lifted from the road surface. To be able to detect both raised and lowered axles and distinguish between them means that the system will work well independent of requirements for total or lowered axles in the classification scheme. Another function is to distinguish double wheels from single wheels, meaning separating four wheel axles from normal two wheel axles. The function finds several characteristic features of the wheels and compares this for all wheels of the vehicle. The outcome is a very robust indication of which individual wheels that are double wheels (see figure 8 and 9 showing the stereoscopic sensor image of vehicles and its number of wheels).

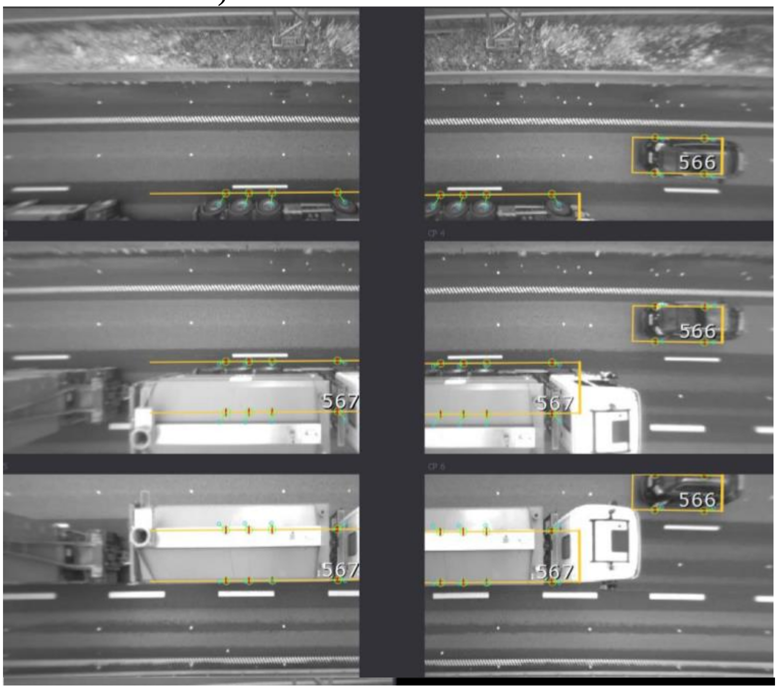


Figure 5 – Axle detection from NVDC sensor with best side view

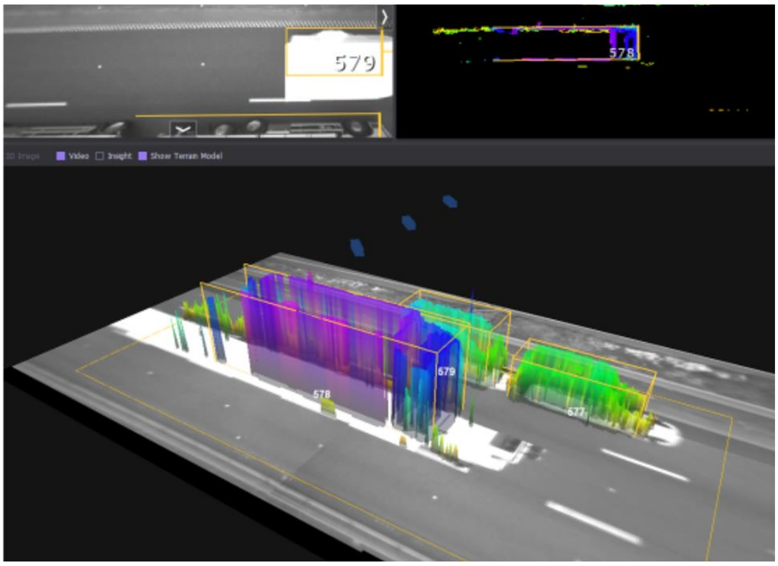


Figure 6 – NVDC example of Axle detection

When Kapsch developed the latest generation of its stereoscopic sensor, called NVDC, the lower mounting position and wider field of view gave a very good side view of vehicles' axles which resulted in the opportunity to develop a novel axle detection method combining video with stereoscopic 3D measurements. By matching the stereoscopic sensor data with the

counted axles by the WIM pavement sensors an almost 99,9% rate of lifted axle detection can be achieved. Furthermore this combination of technologies provides much more better tolerances for stop and go and lane straddling performance than any laser or loop based system.
The performance measurements of the axle detection functions on the test installations show far better results than other evaluated axle detection technologies, and there are still further improvements expected from further tuning of the algorithms. Together with the stereoscopic system's unrivalled detection and volumetric classification performance, the axle detection makes the system's overall classification performance very high for all classification schemes. Performance levels reach values well over 98% for correct number of axles on all vehicles in typical installations. It is interesting to see that for classification schemes where vehicles are grouped in e.g. three or more axles, which is very common in Europe, the results are already very high, whereas for vehicles with five or more axles, the achieved performance is slightly lower. This is a focus area for the continued improvements of the axle detection algorithms.

Table 1 – NVDC axle detection rate

3+	4+	total axles
99,60%	99,40%	98,20%

The table 1 shows results from tests in varying conditions. 3+ means that the classification is divided in “2” and “3 or more” axles. 4+ means that the classification is divided in “2”, “3” and “4 or more axles”. Total axles means that there is no grouping of number of axles in the classification. Totally 5461 passages were evaluated.
Using the combined result of the 2 sub-systems the WIM and the NVDC, it is possible to know the exact number of raised of axles. Further on the WIM sub-system it can be quoted to know, as shown in the graphic above, the axels that are being weighted are the axles that are touching the pavement. On the NVDC side, the axles can be detected by using the stroboscopic images as shown before. So the combination of both, WIM and NVDD technology, provides a high accurate detection rate of raised axles.

5. Conclusion

In a brown field environment, where traffic management or electronic tolling systems are in place, the WIM solution can act as a helpful and cost efficient system, which also allows reuse of existing infrastructure (e.g. gantries, power lines, cabinets, etc.).
So Weigh-In-Motion brings back more safety and security to the roads. Weigh-In-Motion will become an important part to avoid more uncontrolled heavy goods traffic, helps to save money in the maintenance of the roads, reduce environmental impacts as well as provide a fair trade on the road for the future.
In particular according the Brazilian requirements of the law 13.103, article 17, which states that trucks without load do not have to pay toll for axels which do not touch the road, the combination of the two technical solutions WIM and NVDC can detect lifted axles in a high accurate way and provide the relevant information almost in real-time to the relevant authorities for Direct Enforcement.

6. References

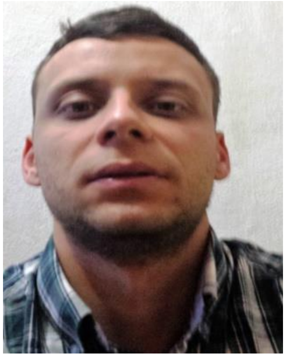
- Jacob, B., O'Brien, E.J. and Jehaes, S. (2002). Weigh-in-Motion of Road Vehicles – Final Report of the COST323.
- Bundesministerium für Verkehr Innovation und Technologie Statistik Straße & Verkehr (January 2016) http://www.bmvit.gv.at/service/publikationen/verkehr/strasse/downloads/statistik_strasseverkehr2016.pdf on 31.03.2016

Session 3 : Data Quality and Accuracy Assessment by Modeling

Chair: Franziska Schmidt (IFSTTAR, France)

MODELLING WEIGH- IN-MOTION SYSTEM BASED ON LOAD CELLS INCLUDING VEHICLE DYNAMICS AND ROAD ROUGHNESS FOR VEHICLE WEIGHING ENHANCEMENT

Graduated in Technology in Industrial Automation at the State University of Rio Grande do Sul, 2006. Currently is a public agent on National Agency of Land Transport in Brazil (ANTT) with over six years of experience in the application of WIM to enforcement and he is Master's student in Mechanical Engineering at UFRGS working on WIM projects.



He has been professor of the Mechanical Engineering Department at Federal University of Rio Grande do Sul, Brazil (UFRGS) since 2003. He received his D.Sc. and M.Sc. degrees in Civil Engineering from UFRGS in 1997 and 2001 respectively. His main research interests include Finite Elements, Uncertainty Quantification and Instrumentation.

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Abstract
This work proposes a numerical study on the behavior of weigh-in-motion systems based on load cells platforms. Some important parameters that may control this behavior that are modeled are: random road roughness, vehicle vertical dynamics, vehicle speed, load platform step's height to the road are some of these parameters. Two types of vehicles that represent a class of load vehicles are modeled travelling at different speeds and being weighted. Ground reaction force and acceleration time history on several DoF are recorded and filtered in order to obtain the static load per axis and the corresponding estimated errors. Conclusions related to the reduction in the accuracy of the measuring system with increased vehicle speed are confirmed in the numerical study, although important conclusions not so obvious concerning the importance of vehicle dynamics and load platform step's height are highlighted.

Keywords: Platform load cells, Weigh-in-motion, WIM, Signal filtering, Signal processing, Vehicle dynamics, Road roughness profile.

Resumo
Este trabalho apresenta um estudo sobre o comportamento de pesagem em sistemas de movimento baseados em plataformas de células de carga. Parâmetros relevantes nesse comportamento são modelados: rugosidade aleatória da pista, dinâmica vertical do veículo e sua velocidade e desnível para a estrada são alguns desses parâmetros. Dois tipos de veículos de uma classe de veículos de carga são modelados trafegando a diferentes velocidades. As forças de reação do solo e históricos de aceleração em vários GDL são registrados e filtrados a fim de obter a carga estática por eixo e os erros nas estimativas do peso. Conclusões relacionadas à redução da precisão do sistema com o aumento da velocidade do veículo são confirmadas, embora importantes conclusões não tão óbvias sobre a importância da dinâmica do veículo, altura da plataforma de pesagem são ressaltadas.

Palavras-chave: Plataforma de células de carga, Pesagem em movimento, Filtragem de sinais, Processamento de sinais, WIM, Dinâmica Veicular, Perfil de rugosidade de pista.

1. Introduction

Nowadays, most of the weigh-in-motion systems (WIM) operating in Brazil are based on load cells for enforcement. The weighing is performed in two stages: (a) first, a selective system is used to separate vehicles that may be overweight. Usually, this system has not sufficient accuracy to fine and it is not measured by a metrological agency, so a few overloaded vehicles may be released; (b) on the second stage, the selected vehicles are weighed at low speed on load cells platforms. Due to uncertainties in the calibration and mechanical system, the vehicle speed is limited to 5-12 km/h. Therefore, accurate weighing at higher speeds is desirable, increasing the number of vehicles that are effectively weighed and not impairing the road flow. By using an effective and suitable weighting system, it is possible to reduce accidents caused by overweight, rollover, and lack of braking capacity and reduce damage to the pavement and increasing the durability of cargo vehicles.

In this paper, the vehicle dynamics, road roughness and the vertical force acting on the measuring system are numerically modelled and investigated in order to evaluate the speed limits for an accurate assessment of vehicle axle load also the of gross vehicle weight (GVW) evaluated using load cells platforms. Besides, the step's height between load cell platform and road are investigated in order to evaluate the effect on measured forces and system accuracy. The main problem is the accurate weight evaluation based on part of the acquired force signal from load cells, which may be superposed to the loads from vehicle's vertical dynamics. Jacob (2011) affirms that there is a typical increase of 10% to 30% in RMS value for good roads and up to 50% to high rough roads. So, this problem is closely related to force signal filtering. Signal reconstruction/filtering methods can be used in WIM technology as B-WIM (Bridge Weigh-in-Motion), on-board weighing or MS-WIM (Multiple-Sensor Weigh-In-Motion) just to name a few. Artificial Neural Networks (ANN), Kalman filters, Moving Average, Butterworth and Adaptive filters (Meller et al., 2014) are examples of such methods. In this paper, it is preliminarily investigated the use of some of these methods (Moving Average, Butterworth).

2. Numerical model

2.1 Simulated and Tested Vehicles

There are two types of vehicles being numerically tested: Type (a), a 8 DoF (degree of freedom) model (with four independent suspensions and driver seat, four unsprung masses, pitch, roll and vertical displacements of the vehicle's body mass) that is suitable for model vans/light trucks; Type (b), a 10 DoF model (with two suspensions bars, driver and passenger seats) that are suitable for bus/medium trucks. Figure 1 shows a sketch for the two numerical models used in this paper. Type (a) vehicle presents a total mass of 2550 kg with no shipping load. It is assumed a wheelbase of 2.312 m. The model includes car body, m_c and by the unsprung masses, m_1, m_2, m_3, m_4, the damping values for the suspension system, c_{12}, c_{22}, c_{32}, c_{42}, and by tire stiffness k_{11},k_{21}, k_{31}, k_{41} and finally the suspension stiffness k_{12},k_{22}, k_{32}, k_{42}. The driver's seat is modeled as single degree of freedom with mass m_a, stiffness k_a and damping c_a. The geometrical parameters are the distance from the center of mass to the front axle a and the distance from the center of mass and the rear axle b. Thus, $a+ b$ is the wheelbase. l is the vehicle width, x_a and y_a are the positions for the driver's seat measured from to the center of mass of the car body. Details related to the equation of motion, further parameters and their values can be found in (Dhremer, 2012).

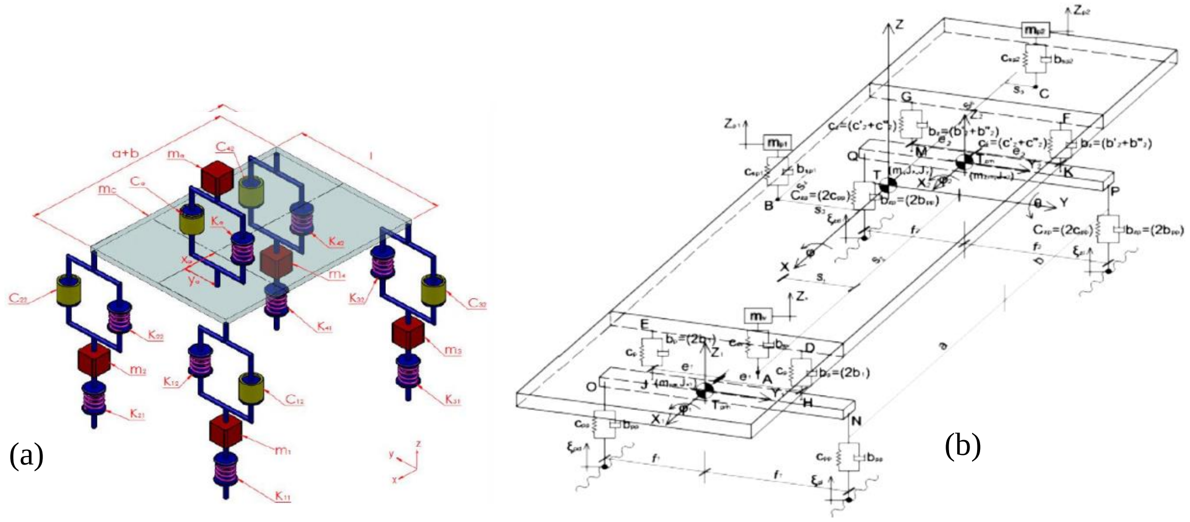

Figure 1– Type (a) vehicle (Dhremer, 2012) and Type (b) vehicle (Sekulic´ *et al*, 2013)

Type (b) vehicle represents and actual passenger bus model IK301 with total mass of 18871 kg, wheelbase of 5.650m and width 2m. The mass parameters are the following: m_v is the mass of the driver's seat, m_{p1}, m_{p2} are the masses for the seat/passengers 1 and 2, only modelled for acceleration purpose. The bus total sprung mass, fully loaded, is represented by m_{pm}. The front and rear axle masses are m_{zm}. The driver's seat has shock-absorber dampers with c_{sv}, stiffness of k_{sv}. Spring stiffness of the driver's seat suspension system k_{vm}. c_{sp1}, c_{sp2} are the passenger's seat damping and k_{sp1}, k_{sp2}, the corresponding stiffness. c_p, k_p means the single air bag damping and stiffness of front axle. More details related to the bus model, equation of motion and values for the parameters can be found in (Sekulic´ *et al*, 2013).

2.1.1 Modal features for the vehicle models

Using an eigenvalue-eigenvector analysis, the vibration mode shapes and modal frequency can be obtained. Table 1 presents those modal frequencies for both vehicles. This information is useful for the analysis and processing of load platform signal.

Table 1 – Modal Frequencies of vehicles

Vehicle	Modal Frequencies (Hz)									
Type (a) (8 DoF)	1.416	1.640	1.713	4.937	9.085	9.114	10.702	10.711	-	-
Type (b)(10 DoF)	1.012	1.093	1.254	1.631	3.373	3.389	8.944	9.507	12.537	13.598

2.2 Road roughness modelling

The road roughness follows ISO 8608 (1995) recommendations that is based on international roughness classes of Power Spectral Density (PSD) for pavement rating. Time histories for the road tracks are simulated and used as input parameters for the vehicle model. The integration interval of the spectral density of the road irregularities is an important parameter to be considered for the correct generation of the roughness profile. In this regard, ISO 8608 (1995) recommends the use of integration interval in the spatial frequency from 0.01 cycle/m up to 2.83 cycles/m in case of usual road profiles. The road roughness ISO 8608 (1995) model, based on Dodds and Robson's works, which is essentially a Homogeneous Gaussian Process (HGP) model, can be stated by Equation (1):

$$G_{\xi}(\Omega) = C(\Omega)^{-w} \tag{1}$$

where G_{ξ} is the single sided power spectral density for road roughness (m^2/cycle/m), Ω means the wave number (cycle/m), C is the general road roughness coefficient (m^3/cycle that can be evaluated as $10^{-6} \times 4^{c_n+1}$ with c_n as the road class), which is related to the road surface condition and w is the wavelength distribution. An improved formulation for the road profile roughness follows the Equation (2):

$$G_\xi(\Omega) = \begin{cases} C(\dfrac{\Omega}{\Omega_0})^{-w_1} & for\ \Omega \le \Omega_0 \\ C(\dfrac{\Omega}{\Omega_0})^{-w_2} & for\ \ \Omega \ge \Omega_0 \end{cases} \tag{2}$$

where the single sided PSD was split into two parts at the discontinuity frequency Ωo (cycle/m). The discontinuity frequency is usually set as Ωo=1/2π=0.16 cycle/m, which corresponds to a wavelength of about 6.3m, a very common value for British roads. w_1 and w_2 are wavelength distribution parameters. Other sophisticated models are available, but they use more parameters to describe the road profile. Instead of following this way, in this paper it will be used the simple model with Ωo=0.1 cycle/m, distribution parameter w1= w2=2.0 and the general road roughness coefficient C=0.01 m^3/cycle in order to make possible comparisons with literature. The function that describes random surface profile, travelled by the vehicle, according to Gomes *et al*. (2008) is a function of displacement as a function of time, consists of a sum of harmonics, as shown the Equation (3).

$$x(t) = \sum_{i=1}^{N} A_i sen(\omega_i t + \varphi_i) \tag{3}$$

where the phase angle is a random variable generated between $0, 2\pi$. The frequency ω_i can be related with the wave numbers n_i and with the speed of horizontal displacement of the vehicle v as follows, Equation (4):

$$\omega_i = 2\pi n_i v \tag{4}$$

The amplitude for each component of the function A_i (shift) is defined as, Equation (5):

$$A_i^2 = \sum_{i=1}^{N} G(n_i)\Delta n_i \tag{5}$$

Thus, the road profile is obtained by Equation (6):

$$x(t) = \sum_{i=1}^{N} \sqrt{G(n_i)\Delta n_i}\, sen(\omega_i t + \varphi_i) \tag{6}$$

As the front and rear tires don't suffer influence of the track at the same time, the entry of the disturbance must be offset with the time needed to traverse the distance between axles by the amount of length between axes divided by v.

2.3 Modelling the step between load platform and road surface

The link between the platform and the track is modeled as a kind bounce step. The deformation of the tire is characterized in the model of the vehicle by their stiffness. For the step modelling purposes, it is assumed the track before and after the load cell has their characteristic roughness. On the surface of the load cell, this roughness is assumed smooth. In order to properly describe the input and output of the load cell must have at least a number of points in space (for example 20 parts in length l_p) to make sure the discretization in space is enough to represent the roughness of the road profile.

At time t_1, the vehicle hit the load platform and at time t_2 the tire is completely on the load platform. At time t_3, the tire is just leaving the platform. r means the tire radius and h the step height that is measured from the mean road level. l_p means the load platform length in the direction of vehicle movement and v is the constant vehicle speed (see Figure 2).

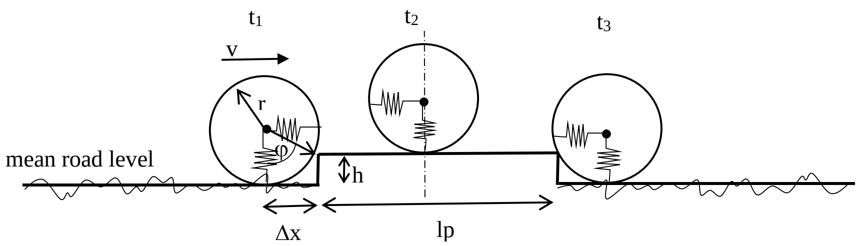

Figure 2 – Sketch of road roughness and step modelling for the load cell platform

2.4 Vehicle Dynamic Analysis and Reaction Forces from Load Platform

The vehicle dynamics including loading from the road roughness and load platform gaps are modelled as usual as external input forces and the equilibrium equation of motion in the discretized form takes the form, Equation (7):

$$[\mathrm{M}]\ddot{\mathbf{x}}(t)+[\mathrm{C}]\dot{\mathbf{x}}(t)+[\mathrm{K}]\mathbf{x}(t)=\mathbf{F}(t) \tag{7}$$

where $\mathbf{F}(t)$ mean the load vector (including self-weigh and forces imposed by the road to the tires, [M] is the structural mass matrix, [C] is the structural damping matrix and [K] structural stiffness matrix. The displacements vector is represented by $\mathbf{x}$ and the corresponding derivatives by $\ddot{\mathbf{x}}$ and $\dot{\mathbf{x}}$. For the numerical integration of the 2nd order coupled differential equation system, an implicit Newmark scheme was used. According to Rao (2010), the stability of the method depends on the parameters α and β. They are choose as $\alpha \geq 0.25(\beta+1/2)^2$ and $\beta \geq 0.5$ in order to assure stability. The recurrent equation for the analysis and DoF history record are the following, Equation (8):

$$\begin{aligned}
\boldsymbol{x}_{i+1} &= \left[\frac{1}{\alpha(\Delta t)^2}[\mathrm{M}]+\frac{\beta}{\alpha(\Delta t)}[\mathrm{C}]+[\mathrm{K}]\right]^{-1}\left\{\mathrm{F}_{i+1}+[\mathrm{M}]\left(\frac{1}{\alpha(\Delta t)^2}\boldsymbol{x}_i+\frac{1}{\alpha(\Delta t)}\dot{\boldsymbol{x}}_i+\left(\frac{1}{2\alpha}-1\right)\ddot{\boldsymbol{x}}_i\right)\right.\\
&\qquad\left.+[\mathrm{C}]\left(\frac{\beta}{\alpha(\Delta t)}\boldsymbol{x}_i+\left(\frac{\beta}{\alpha}-1\right)\dot{\boldsymbol{x}}_i+\left(\frac{\beta}{\alpha}-2\right)\frac{\Delta t}{2}\ddot{\boldsymbol{x}}_i\right)\right\}\\
\dot{\boldsymbol{x}}_{i+1} &= \dot{\boldsymbol{x}}_i+(1-\beta)\Delta t\ddot{\boldsymbol{x}}_i+\beta\Delta t\ddot{\boldsymbol{x}}_{i+1}\\
\ddot{\boldsymbol{x}}_{i+1} &= \frac{1}{\alpha(\Delta t)^2}(\boldsymbol{x}_{i+1}-\boldsymbol{x}_i)-\frac{1}{\alpha(\Delta t)}\dot{\boldsymbol{x}}_i-\left(\frac{1}{2\alpha}-1\right)\ddot{\boldsymbol{x}}_i
\end{aligned} \tag{8}$$

The choose time interval is based on road roughness accuracy representations and this results in time intervals several orders of magnitude lower than usual($\Delta t=10^{-3}$s) values assuring good precision to the resulted values.

3. Performed tests

In order to represent a real situation to assess the WIM system accuracy, several simulations were performed using different road roughness, vehicle speeds, load platform step's height and vehicle type. This intends to capture the main features in a simulated weighing system. For a defined combination of parameters, the tests consisted on 100 simulations representing the actual variability of the weighting system and using Equation (9) to evaluate the system accuracy. Random generation of road roughness and parameters allowed the variability between simulations. The system accuracy is assessed following the COST323 (Jacob *et al.*, 2002): "for each entity (gross weight, single axle, group of axles and axles of a group) the individual relative errors with respect to the static load (weight) or accepted reference values" are calculated as x_i:

$$x_i=\frac{(Wd_i-Ws_i)}{Ws_i}\times 100 \quad (in\,\%) \tag{9}$$

where Wd_i and Ws_i are the in-motion measured value and the static (reference) value". After numerical simulations, the mean error, standard deviation, maximum error and RMS error were evaluated for each axle and GVW for each type of vehicle. For the case of weight error per axle, it presented the mean error value for the two axles.

3.1 Step height effect

In this test, the step height was varied from -8 mm to +8 mm for constant vehicle speed and road class. The two vehicle types were tested. Tables 2 and 3 shows the numerical values obtained in this test for vehicle type (a) and vehicle type (b), respectively.

Table 2- GVW and weight per axle errors for step height variation for vehicle type (a)

TYPE (a) VEHICLE, SPEED=40 Km/h AND Cn=2 (ROAD CLASS "B")								
	Gross vehicle weight				Weight per Axle			
Step	Mean Error	RMS Error	Max. Error	Std. Dev.	Mean Error	RMS Error	Max. Error	Std. Dev.
-8mm	-9.89%	11.35%	-22.77%	5.59%	-10.04%	11.52%	-23.16%	5.67%
-4mm	-5.31%	7.82%	-22.04%	5.77%	-5.39%	7.94%	-22.33%	5.85%
-2mm	-2.42%	7.66%	-20.71%	7.31%	-2.46%	7.78%	-21.04%	7.78%
2mm	3.28%	7.84%	17.82%	7.15%	3.33%	7.94%	18.01%	7.24%
4mm	5.02%	8.25%	23.05%	6.58%	5.09%	8.37%	23.46%	6.68%
8mm	10.16%	11.92%	23.42%	6.27%	10.32%	12.12%	23.86%	6.38%

Table 3- GVW and weight per axle errors for step height variation for vehicle type (b)

TYPE (b) VEHICLE, SPEED=40 Km/h AND Cn=2 (ROAD CLASS "B")								
	Gross Vehicle weight				Weight per Axle			
Step	Mean Error	RMS Error	Max. Error	Std. Dev.	Mean Error	RMS Error	Max. Error	Std. Dev.
-8mm	-10.90%	12.30%	-25.39%	5.74%	-11.09%	12.53%	-25.39%	5.85%
-4mm	-5.72%	9.31%	-19.49%	7.38%	-5.81%	9.44%	-20.00%	7.49%
-2mm	-2.47%	7.42%	-17.00%	7.03%	-2.49%	7.50%	-17.47%	7.11%
2mm	3.24%	7.78%	20.41%	7.11%	3.26%	7.88%	20.66%	7.21%
4mm	6.72%	9.84%	20.87%	7.22%	6.83%	9.96%	21.09%	7.29%
8mm	10.62%	12.52%	24.80%	6.67%	10.84%	12.76%	25.25%	6.76%

It was verified that for both vehicles types (a) and (b) the step height is an important factor. It is clear that for a large flow of vehicles measured by a load platform, step variations are expected mainly for systems with low maintenance. This can decrease accuracy with the use of the WIM system. For the GVW mean error, as indicated by Figure 3, it was observed a similar linear behavior for both vehicle types that is function of the step height. The mean error of weight per axle presented values slightly higher, but the overall linear behavior was preserved. For vehicle type (a) it was observed error that are slightly lower than those for type (b) vehicle, especially for ± 8 mm step height.

3.2 Vehicle speed effect

This test presents the results of weight errors in case of vehicle speed variations. It was assumed five different vehicle speeds from 10 km/h to 80 km/h. The road class and step height were fixed. Tables 4 and 5 show the weight errors for vehicles type (a) and (b), respectively.

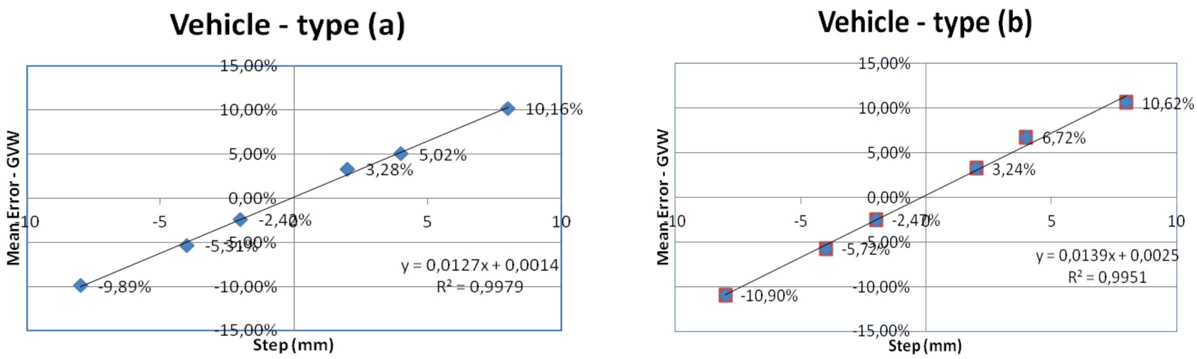

Figure 3 – Mean Error–GVW × step height: type (a) vehicle and type (b) vehicle.

Table 4- GVW and weight per axle errors for vehicle speed variation and vehicle type (a)

TYPE (a) VEHICLE, STEP SIZE=2 mm AND Cn=2 (ROAD CLASS "B")								
	Gross vehicle weight				Weight per Axle			
Speed	Mean Error	RMS Error	Max. Error	Std. Dev.	Mean Error	RMS Error	Max. Error	Std. Dev.
10 Km/h	0.71%	2.73%	7.89%	2.65%	0.72%	2.74%	7.85%	2.65%
20 Km/h	1.06%	3.95%	10.52%	3.82%	1.07%	3.98%	10.58%	3.98%
40 Km/h	3.28%	7.84%	17.82%	7.15%	3.33%	7.94%	18.01%	7.24%
60 Km/h	4.95%	9.75%	22.98%	8.44%	5.02%	8.55%	23.23%	8.55%
80 Km/h	5.55%	12.74%	29.73%	11.52%	5.63%	12.91%	30.15%	11.67%

Table 5- GVW and weight per axle errors for vehicle speed variation and vehicle type (b)

TYPE (b) VEHICLE, STEP SIZE=2 mm AND Cn=2 (ROAD CLASS "B")								
	Gross vehicle weight				Weight per Axle			
Speed	Mean Error	RMS Error	Max. Error	Std. Dev.	Mean Error	RMS Error	Max. Error	Std. Dev.
10 Km/h	0.25%	0.70%	2.36%	0.66%	0.23%	0.68%	2.25%	0.64%
20 Km/h	1.12%	3.06%	7.21%	2.86%	1.15%	3.15%	7.46%	2.95%
40 Km/h	3.24%	7.78%	20.41%	7.11%	3.26%	7.88%	20.66%	7.21%
60 Km/h	4.96%	10.91%	35.54%	9.77%	4.92%	10.87%	35.41%	9.74%
80 Km/h	6.19%	13.93%	42.11%	12.54%	6.13%	13.82%	41.70%	12.45%

One can notice that both vehicle types (a) and (b) presented for this speed span a good linear fit for the GVW error × vehicle speed and this is shown by Figure 4. Either the relation between standard deviation and vehicle speed as the mean weight error per axle and the corresponding standard deviation presented a similar linear behavior. Both vehicles presented similar behavior regarding the RMS error, except for large speeds where the vehicle (b) presented RMS errors slightly greater than vehicle (a). However, for the case of low speeds, vehicle (a) presented RMS error greater that vehicle (b). It was observed that for higher speeds (>80km/h) some nonlinear trends and the RMS error increase with a lower slope.

3.3 Road roughness effect

This test was meant to check the weight errors for different road class. It was varied the road class from A to E (A mean a very smooth good road and E, a poor quality road. The vehicle speed and step height were fixed. Tables 6 shows the numerical results for the simulation for vehicle type (a) and Table 7 for vehicle type (b), respectively.

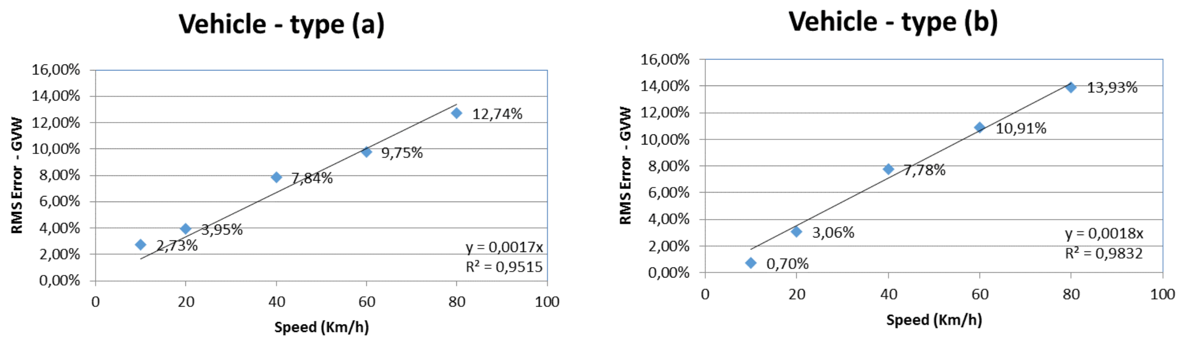

Figure 4 – RMS Error –GVW × vehicle speed: type (a) and type (b) vehicles

Table 6- GVW and weight per axle errors for road class variation and vehicle type (a)

TYPE (a) VEHICLE, STEP SIZE=2mm AND SPEED=40 Km/h.								
	Gross vehicle weight				Weight per Axle			
Road Class	Mean Error	RMS Error	Max. Error	Std. Dev.	Mean Error	RMS Error	Max. Error	Std. Dev.
A (C_n=1)	3.05%	4.74%	14.04%	3.64%	3.10%	4.81%	14.22%	3.70%
B (C_n=2)	3.28%	7.84%	17.82%	7.15%	3.33%	7.94%	18.01%	7.24%
C (C_n=3)	3.60%	13.95%	30.98%	13.54%	3.64%	14.13%	31.58%	13.73%
D (C_n=4)	7.14%	29.11%	75.18%	28.36%	7.27%	29.54%	76.37%	28.78%
E (C_n=5)	6.94%	48.21%	126.22%	47.95%	7.07%	48.95%	128.21%	48.68%

Table 7- GVW and weight per axle errors for road class variation and vehicle type (b)

TYPE (b) VEHICLE, STEP SIZE=2mm AND SPEED=40 Km/h.								
	Gross vehicle weight				Weight per Axle			
Road Class	Mean Error	RMS Error	Max. Error	Std. Dev.	Mean Error	RMS Error	Max. Error	Std. Dev.
A (C_n=1)	3.12%	4.85%	13.95%	3.73%	3.14%	4.90%	14.04%	3.78%
B (C_n=2)	3.24%	7.78%	20.41%	7.11%	3.26%	7.88%	20.66%	7.21%
C (C_n=3)	4.39%	14.58%	36.86%	14.12%	4.45%	14.73%	37.15%	14.12%
D (C_n=4)	4.38%	26.38%	70.29%	26.14%	4.47%	26.68%	71.61%	26.43%
E (C_n=5)	3.01%	66.56%	173.02%	66.83%	3.06%	67.31%	175.70%	67.58%

One can notice by Figure 5 that both vehicles type (a) and type (b) presented a good exponential fit for GVW RMS error × class road. The GVW standard deviation presented a similar exponential behavior. For road classes D and E the overall errors were very high and this shows this class roads should not be used in the high-speed WIM systems.

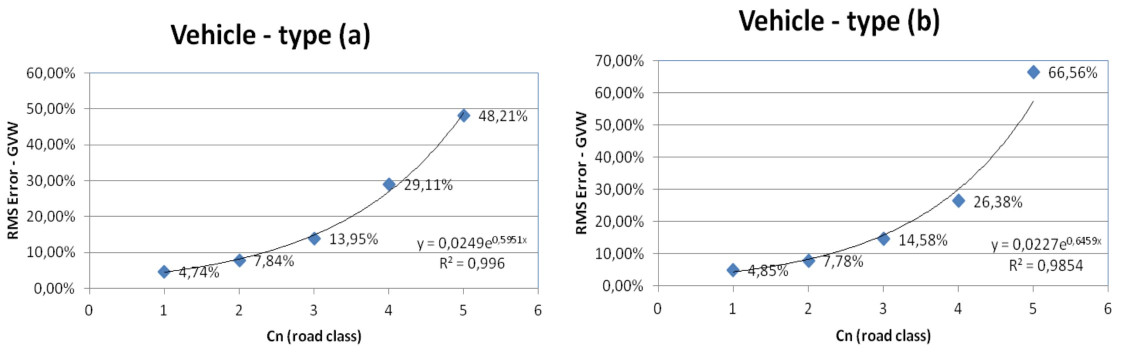

Figure 5 – RMS Error –GVW × Road Class: type (a) and type (b) vehicles

4. Signal processing and analyses

4.1 Frequency content in reaction forces due to vehicle-road interaction

This study aims to check the frequency content due to vehicle-road interaction. The complete test campaign is not shown here due to space requirements. Only a class road of C_n=2, vehicle speed 40 Km/h, step height +4 mm type (b) vehicle. Figure 6 shows a sample of the road track and the corresponding time history of reaction force for the front right tire. On can note the platform step on the road track and the resulting force on the tire force history.

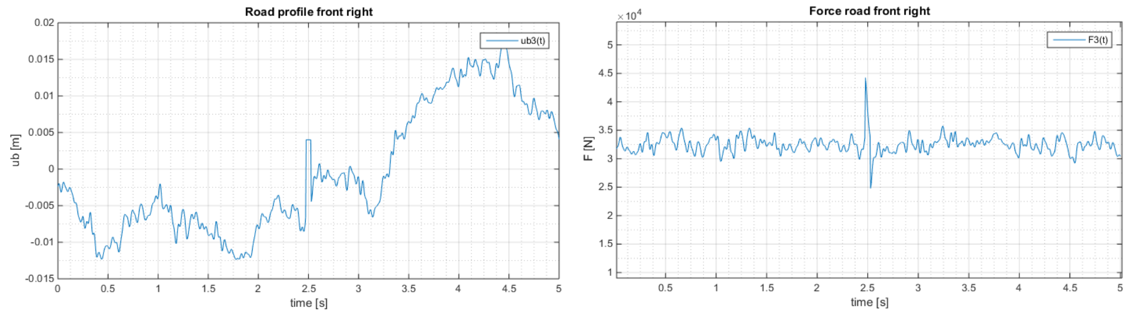

Figure 6 – Road profile and load platform and tire reaction force (front right tire)

The Fast Fourier Transform (FFT) of the tire force history was performed in order to check the frequency content of the force signal (Figure 7). Some of the natural frequencies of the numerical model were found in the corresponding graphs indicating that the vehicle vibrates at some of the natural frequencies (impact on the load platform). Other important peaked values are due to road excitation (e.g., 21 Hz for type (a) vehicle). Frequencies above 40 Hz are not significant for both type (a) and type (b) vehicles for a vehicle speed of 40 Km/h.

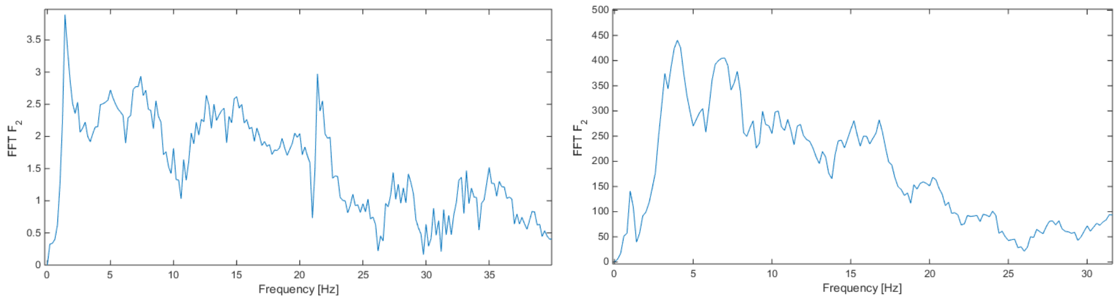

Figure 7 – FFT of tire force: type (a) (in the left) and type (b) (in the right)

4.2 Signal processing effects

In this test, the effect of signal processing of the acquired signals by the load platform is examined. Some tests were performed in order to filter noise and cancel dynamic effects of the vehicle vibration in the force signal. The filter design should be meant to minimize the RMS error and will depend on the vehicle dynamics, noise level and step height, vehicle speed, road class etc. Using a road class B, a step height of 4 mm and vehicle speed of 40 Km/h (a typical operating mean speed of a selective system in Brazil) several tests were performed. In this case, the RMS errors decreased in RMS value from 8.50% to 5.80% for vehicle type (a) and from 9.95% to 7.73% for a vehicle type (b). The future work of the research is related to the use ANN and heuristic algorithms to optimize the filtering techniques in order to get a decrease in the RMS error. The identification of the boundaries of the measured force signal may give guidance on the actual correction of the measured force signals. The use of adaptive filters are also being used with relative success in the identification of vehicle's dynamic and better weight estimation.

5. Final remarks

With the gradual increase in the number of vehicles on highways, it is important to increase the speed limit for WIM systems. In this work, the main finding is that it is possible to obtain some accuracy, weighing with speeds greater than the usual 5 km/h in Brazil. At least theoretically, the weighing methodology based on load platforms may be improved starting from a new calibration methodology and use of improved signal processing methods. Furthermore, it is expected that such improvements may allow the use of more accurate selective scales, preventing the traffic of overweight vehicles.

However, there are difficulties. Weighing at very high speeds using just one platform seems to be very complicated. Braking on the platform can induce other dynamic problems in the measurements. Higher speeds means small-acquired force signals for a fixed length platform. This will difficult the accurate filtering/reconstruction and thus, weight evaluation. Other types of vehicle models are expected to be analyzed in future works. Experimental tests are foreseen in order to verify the numerical results and the study of new reconstruction/filtering techniques are also envisioned for future research.

6. Acknowledgements

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DEVELOPMENT OF A WIM DATA QUALITY MANAGEMENT SYSTEM FOR THE BRAZILIAN FEDERAL ROAD NETWORK





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Abstract

Since the start of the present decade, the Brazilian federal government expanded its use of WIM systems for highway planning and operations, and over 350 new high-speed WIM sites should be implemented by the National Department of Transportation Infrastructure (DNIT) by 2017. Motivated by this situation, DNIT and the Transportation and Logistics Laboratory at the Federal University of Santa Catarina (LabTrans/UFSC) developed a prototype of an automated data quality management system, capable of performing effective and efficient quality management of the federal WIM network in Brazil. This paper describes the development of quality criteria adapted to the Brazilian road traffic conditions, their implementation in standard quality checks and the construction of a prototype computer tool for automated data quality management.

Keywords: Weigh-in-Motion, WIM, data quality, quality management.

Resumo

Com o início da presente década, o governo federal Brasileiro expandiu o uso de sistemas WIM para planejamento e operações de rodovias, e mais de 350 novos sistemas WIM de alta velocidade devem ser implementados pelo Departamento Nacional de Infraestrutura de Transportes (DNIT) até 2017. Motivados por esta situação, o DNIT e o Laborátório de Transportes e Logística da Universidade Federal de Santa Catarina (LabTrans/UFSC) desenvolveram um protótipo de sistema automatizado de gestão de qualidade de dados, capaz de realizar uma gerência efetiva e eficiente da qualidade da rede federal de sistemas WIM. Este artigo descreve o desenvolvimento de critérios de qualidade adaptados às condições do tráfego rodoviário no Brasil, a sua aplicação em verificações de qualidade e a construção de uma ferramenta para gestão automatizada da qualidade dos dados.

Palavras-chave: Pesagem em movimento, WIM, qualidade de dados, gestão da qualidade.

1. Introduction

In the present decade, motivated by a new wave of investments in road infrastructure, the Brazilian Federal Department of Transportation Infrastructure (DNIT) focused its attention on modernizing its methods for traffic data collection and truck weight enforcement with the objective of providing more effective tools for roadway planning and operations. In this context two national programs were launched:

- PNCT - the National Plan on Traffic Count with the objective of providing permanent traffic data collection in its road network and therefore improve decision-making for investments in transportation infrastructure in Brazil. The PNCT consists of 320 traffic data collection sites equipped with WIM systems throughout the federal road network and;
- PIAF - the Integrated and Automated Enforcement Stations, which consists of fixed weigh stations with mainline WIM for screening of heavy vehicles. In its first phase, 35 PIAFs have been contracted for weight enforcement and operations are expected to start in 2017.

Experience with the use of WIM systems show that system performance generally decays over time, and these changes in performance have an effect on the accuracy and reliability of the output of WIM systems. As WIM data will be used as input for different kinds of studies and political decision making processes, the quality of these processes is directly dependent on the quality of the WIM data collected. As a consequence, the establishment of effective methods and tools for monitoring the quality of the WIM data collected is important in order to ensure the quality of the results and conclusions drawn from the application of this data.

DNIT endorsed a project in collaboration with LabTrans and the consultancy of Corner Stone International for the development of a prototype automated data quality management system capable of performing effective and efficient quality management of its WIM network. The project was divided into three main parts:

- Development of potential quality criteria based on international experience and validation under Brazilian conditions.
- Implementation of statistical control charts based on quality criteria.
- Implementation of prototype software tool.

2. Development of Quality Criteria

For the development of quality criteria suitable for the Brazilian federal WIM network, a study was conducted on existing WIM Quality Checks developed in different countries. Research and applications from South Africa (De Wet, 2012), (Slavik, De Wet, 2012), the United States (Nichols, Bullock, 2004), (FHWA, 2010) and the European Union (Telman, Hordijk, 2013), (Lees, Van Loo, 2015) were analyzed with the objective of identifying potential standard checks that could be adapted for Brazilian conditions. As a result of this process, the following criteria were selected:

2.1 Traffic Count

The number of registrations per day will vary from day to day because of variations in the traffic flow. However a full day or a number of hours without any registrations is an indication that the system may have been offline. Monitoring the number of heavy vehicles records per hour serves as a criterion to detect if the system has been offline for longer periods. If a system has been offline for too long, it reduces the reliability of the collected data.

The PNCT and PIAF are programs developed under the design-build-operate-maintain (DBOM) contracting model, which means that a private third-party is responsible for the design and construction as well as operation and maintenance-related services. While the PIAF has not yet been implemented, the PNCT establishes that a contractor will be penalized if there is an absence of records in over 10% of the total hours in a month.

Initial assessments of monthly sets of data from PNCT have shown that some of sites presented ‘gaps’ in the data collection, indicating that the system had been offline for several days. The initial monthly check on traffic count will result in a warning if more than 72 hours are registered with no vehicle records in a given month. Later implementations may incorporate further quality checks based on vehicle counts per hour and per day, which have been used for similar purposes in different countries (Walker, Cebon, 2012).

2.2 Vehicle Classification

The distribution of vehicles over the various vehicle classes will vary from system to system because of variations in the traffic flow. The class ‘other’ is generally intended for special transports with extended axle configurations that do not match any other vehicle class. However it is also used by WIM systems for unclassified vehicles, which provides an indication of the incorrect operation of the WIM system itself (Van Loo and Lees, 2015).
According to the Brazilian National Register of Commercial Road Vehicles (2015) the fleet of special and operational vehicles that do not fall under the established vehicle classes account to approximately 0.06% of the total registered fleet of heavy vehicles. Thus, it is unlikely that over 10% of the traffic flow will account to special vehicles under normal operating conditions. Assessments of data from a number of PNCT sites have shown sites with up to 50% of heavy vehicles classified as ‘other’ (Class L1), while sites in good operating conditions had percentages as low as 0,8%.

Further evaluation over PNCT sites with more than 10% of heavy vehicles classified as ‘others’ have shown an indication of issues in the measurements of axle distances, which constitutes one of the most important inputs for the PNCT class division. The investigation showed that in all of these cases, at least 90% of the vehicles classified as ‘others’ had at least one of its axle distances measured below 1.00m, while Brazilian regulations establish a minimum of 1,20m for heavy vehicles (DNIT, 2012). Therefore the initial checks implemented in the system will generate a warning if over 10% of the detected vehicles are classified as “others” in two or more consecutive days of a given month.

2.3 Axle Distance

Accurate timing is crucial in any WIM system since it forms the basis for many of its measurements and calculations, like speed, axle distances, length, classification and axle loads. Monitoring of standard axle distances – generally the distance between the 2nd and 3rd axle of a six axle tractor semi-trailer combination - may be used as a possible indicator of failure in the internal timing of WIM systems (Slavik, 2012). This distance is determined by the standardized design and construction of this type of truck that has been optimized for maximum load carrying capacity. As a result, this axle distance will typically show very little variation.

In order to be effective this check needs a statistically significant number of vehicles, hence a very common vehicle class. The first analysis of a month of data from a number of PNCT sites have confirmed that the six axle tractor semi-trailer combination (Class E1 in PNCT and Class 3S3 in PIAF class division) suitable for this type of criteria besides being one of the most common vehicle classes in all sites. In the analysis it was verified that most sites had an average axle distance of between 125 and 126cm with a standard deviation of less than 2%.

2.4 1st Axle Load

International research shows that measurements of the first (steering) axle loads of 5 and 6 axle articulated vehicles may serve as criteria for quality checks on WIM performance. The design and load distribution of this type of vehicle makes the load on the first axle relatively stable and can serve as a reference value. Tests and evaluations performed over WIM data in Brazil indicate that Class E1 in PNCT (Class 3S3 in PIAF class division) is the most suitable for this type of criteria. The graph on Figure 1 presents the distribution of first axle loads of E1/3S3 trucks over the period of two weeks at a fixed low-speed enforcement axle scale:

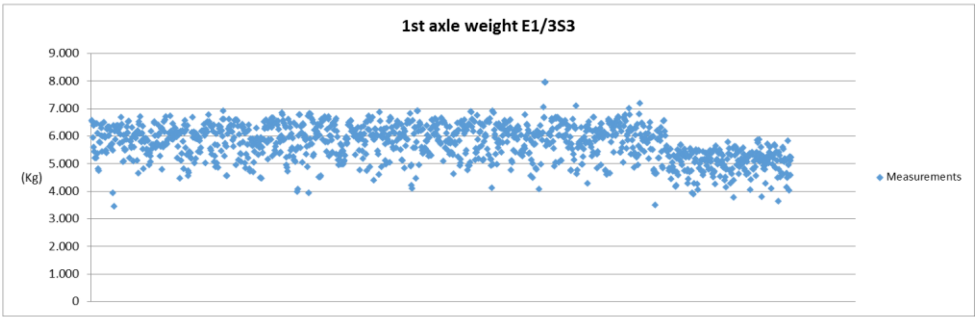

Figure 1 – First axle load distribution - Class E1/3S3– Weigh Station 1608

The average load of the first axle of the 1.282 vehicles of Class E1/3S3 that entered the station was 5.725kg with a standard deviation of 650kg. The graph shows a downward shift in the measurements at the same time when the enforcement officers claimed operational issues with the equipment.

2.5 Validation of Quality Criteria

At this stage, the first set of quality criteria were validated using up to five months of data from PNCT sites. The graph in Figure 2 shows an example of application of the preliminary methodology where daily averages were calculated over a period of two months. In this example, the WIM site is composed by an array with two lines of piezoelectric sensors.

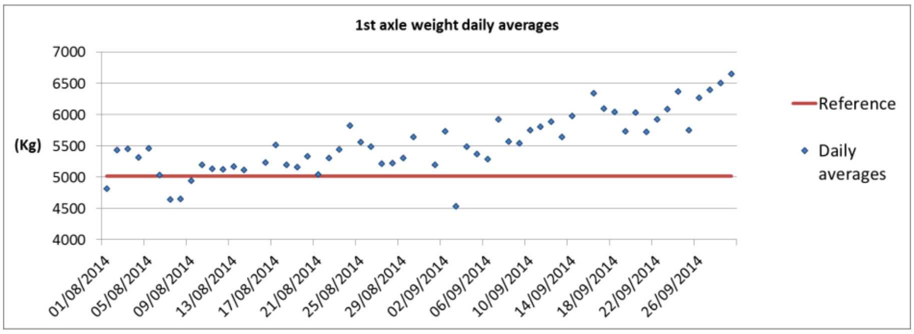

Figure 2 – Daily averages of first axle loads - Class E1 - Site 40046 (PNCT) - Lane 1

The graph on Figure 2 shows the calculation of daily averages of first axle loads of six-axle articulated heavy vehicles over the period from the August to September, 2014. This site started operations in May and the reference line was drawn based on the averages of the first month of data collection. The charts for the site present a relatively steady trend around the reference line until the end of August. In the end of August and especially throughout September, the daily averages started running further above the reference line, showing a possible deterioration in the performance of the WIM system and the potential of the quality check as a tool for detecting shifts in WIM data under Brazilian local conditions.

Besides the evaluations for the development of quality checks based on first axle loads, similar evaluations were performed for checks on axle distance, classification and traffic count processes. Hence, this stage of the analyses presented specific results that confirmed initial assumptions regarding the suitability of certain quality checks, which supported the execution of further analyses and developments.

3. Implementation of quality control charts

The control charts for WIM data quality management were structured through the adaptation of Statistical Process Control (SPC) techniques. In this context, Statistical Control Charts are SPC tools that aim to detect abnormal variation due to circumstances that are not usual or inherent in regular processes. In this methodology, the control charts take into consideration the 1st Axle Load and Axle Distance WIM quality criteria, which are both applied with six-axle tractor-semitrailer vehicle combinations (Class E1 or 3S3). These control charts are based on the theory of Shewart's control charts for variables (Montgomery, 2004), and the application of the quality checks are performed through two distinct phases:

- Phase I – Qualification of reference period.
- Phase II – Evaluation of subsequent months of data collection.

3.1 Phase I

Phase I is performed for the first full month of data collection, immediately after the calibration of the system. This period will be used as a reference for subsequent monthly quality checks, so the consistency of the data is validated with the aid of charts based on daily averages and standard deviations in combination with their respective lower and upper control limits. Due to natural variation in local traffic conditions, the daily subgroups of data vary in size, so the calculations of the central lines and the control limits take that into consideration. The formulations for obtaining the upper and lower limits in Phase I are shown on Table 1:

Table 1 – Phase I – Formulations for control charts

Chart	Lower Control Limit	Upper Control Limit	Central Line
Averages ($\bar{x}$)	$\bar{\bar{x}} - \dfrac{k}{c_4 \times \sqrt{n}} \times \bar{s}$	$\bar{\bar{x}} + \dfrac{k}{c_4 \times \sqrt{n}} \times \bar{s}$	$\bar{\bar{x}}$
Standard deviations (s)	$\left(1 - \dfrac{k}{c_4} \times \sqrt{1 - {c_4}^2}\right) \times \bar{s}$	$\left(1 + \dfrac{k}{c_4} \times \sqrt{1 - {c_4}^2}\right) \times \bar{s}$	$\bar{s}$

- $\bar{\bar{x}}$ and $\bar{s}$ refer to the mean of the subgroup averages and standard deviations, respectively;
- n refers to the number of measurements per day;
- c4 is a control chart constant that depends on subgroup size:

$$c_4 \cong \frac{4\times(n-1)}{4\times n-3} \tag{1}$$

- k refers to the number of standard deviations to be drawn from the central line. Theory of control charts states that for an industrial context with limited common cause variation, the default value for k is 3. For control charts outside the industrial context with a larger expected variation, a higher value for k can be chosen in order to minimize false warnings. Thus, the calculation of the control limits in this methodology considers k = 4 and 5 for the Axle Distance criteria and the 1st Axle Load criteria, respectively.

The establishment of the k values was based on empirical analyses and validation performed over samples of WIM data in the scope of the project. These values were effective in providing limits for the detection of unusual data variation without excessive false warnings. Different values, however, may be adopted as further operation and validation takes place.

Figure 3 shows validation results of Phase I with the 1st axle criteria and WIM data from the Araranguá WIM test-site managed by LabTrans in cooperation with DNIT. In this case, the WIM site is composed by two lines of piezoquartz sensors:

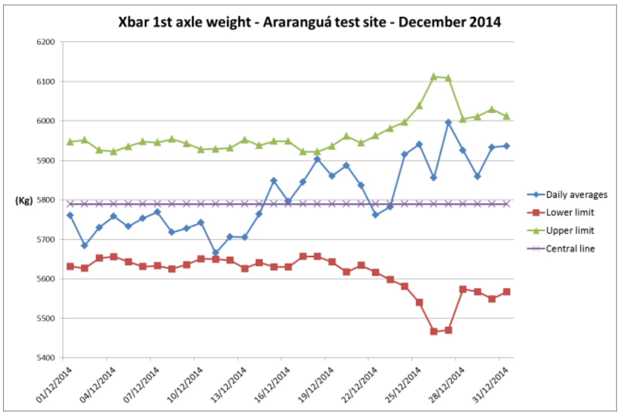

Figure 3 – Phase I - Daily averages of 1st axle loads – E1/3S3 – Araranguá test site

In the chart, all points fall inside the established limits and the period is qualified as a reference for the given criteria. The chart shows a widening of the control limits between December 22nd and December 31st, which is due to the low volume of heavy vehicles during the holiday season. The reliability of the checks becomes lower with a smaller amount of measurements, so the method takes this into consideration and makes the control limits less strict. Besides the quality check performed through control charts, the qualification of the reference period in Process I is done with an extra set of fixed absolute limits in order to verify basic calibration of the system:

- 1st Axle Load criteria: $\bar{\bar{x}}$ < 4000 or $\bar{\bar{x}}$ > 7000.
- Axle Distances criteria: $\bar{\bar{x}}$ < 120 or $\bar{\bar{x}}$ >140.

According to the established methodology, quality checks on the reference month of data will generate a quality warning if one point falls outside the control limits.

3.2 Phase II

Phase II involves quality checks on data collected in the months after the reference period. The formulations for obtaining the upper and lower limits are shown in Table 2, where $\sigma = \bar{s}$

and $\mu = \bar{\bar{x}}$, as previously calculated. The values of k and the formulation for c4 remain the same as in phase I.

Table 2 – Phase II – Formulations for control charts

Chart	Lower Control Limit	Upper Control Limit	Central Line
Averages ($\bar{x}$)	$\mu - \frac{k}{\sqrt{n}} \times \sigma$	$\mu + \frac{k}{\sqrt{n}} \times \sigma$	μ
Standard deviations (s)	$\left(c_4 - k \times \sqrt{1 - c_4{}^2}\right) \times \sigma$	$\left(c_4 + k \times \sqrt{1 - c_4{}^2}\right) \times \sigma$	$c_4 \times \sigma$

The control charts for the subsequent months of WIM data collection will generate a quality warning if a run of 3 consecutive points occurs outside of the control limits, which may indicate a trend in the WIM data. Figure 4 shows the application of Phase II as part of the validation tests of the methodology:

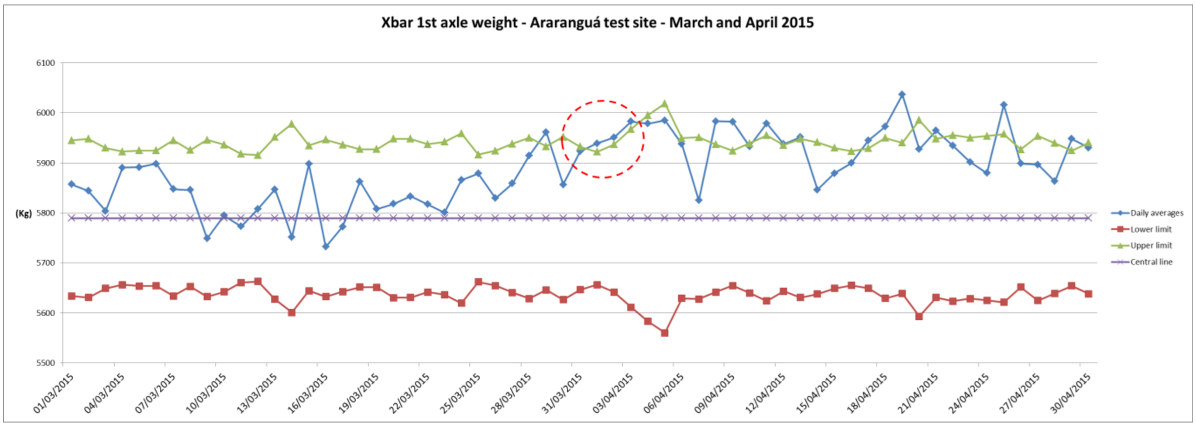

Figure 4 – Phase II - Daily averages of 1st axle loads – E1/3S3 – Araranguá test site

The figure shows a merge of control charts for the months of March and April, 2015. In the given data collection process, the daily averages of the reference vehicle 1st axle loads remained relatively stable until the end of March, but with a slight upward trend. In the first three days of April a run of 3 consecutive points occurred outside the control limits, generating a quality warning. An assessment of the performance of that WIM site with hundreds of measurements from the low-speed enforcement site nearby confirmed an upward shift in the system's weight measurements. The mean difference in GVW measurements from both systems went from 2.28% in March to 3.21% in April. These results indicate the potential effectiveness of the quality check in pointing out trends in the WIM data.

3.3 Performance tests

The chosen quality checks and control charts were implemented in a prototype computer tool and their performance was assessed using up to 12 months of data from PNCT and the Araranguá WIM test site. The main conclusions drawn from these tests were:

- For checks on 1st axle loads, the control charts based on daily averages showed to be valid for detecting shifts in the accuracy of the data collected. Tests with control charts based on standard deviations were tested and need further evaluation before being implemented due to excessive generation of false warnings.

- For checks on axle distances, the validation tests indicate that control charts based on standard deviations appeared to be best suitable for detecting possible system inconsistencies. Control charts based on averages were mostly stable and therefore unable of detecting inconsistencies in axle distance measurements, so further evaluation needs to be done for this type of quality check.
- For checks on vehicle classification, it was verified that the percentage of heavy vehicles classified as 'others' is a suitable criteria. It remains around 1% in sites with good operating performance and can reach up to 59% in other sites. It was found that most sites with high numbers of unclassified vehicles also presented inconsistencies in its axle distances. Furthermore, there is indication of a direct correlation between vehicles being not classified with the detection of axle distances smaller than 1.00m.
- For checks on traffic count, validations showed that the checks were able to identify gaps in the data and are especially relevant for large WIM programs like the PNCT, where significant loss of data can been prevented if detected in earlier stages.

4. Development of a prototype computer tool

A prototype computer tool was developed in order to automate the application of the developed quality checks and facilitate the overall management of data quality. The large volume of data received motivated a careful decision on the programming language and the database tool to be used.

The chosen programming language was Python. For the database, in order to prevent performance issues due to the large volume of data processing, the solution was found in non-relational databases, which are often faster than traditional databases (Nayak et al., 2013).

4.1 Data model and Flow

Figure 5 represents the basic flow of data inside the application, and names a few of the processes involved in the transformation of this data. The whole process is presented in general terms as follows:

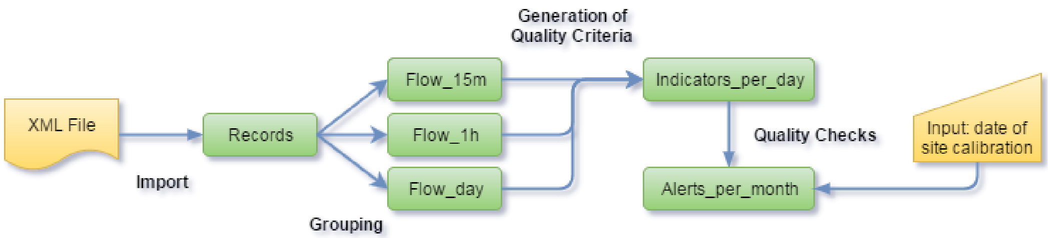

Figure 5 – General data flow diagram within the application

- New data is given to the software via processing of XML files. In a first stage, the software reads all records from the XML file and insert them into the database under a table named 'Records'.
- After processing the XML file, the data that was inserted is read again to perform a grouping operation that joins all the readings in periods of fifteen minutes, one hour and one day (only daily groupings are of interest to the quality assurance criteria). When performing such groupings, a summary containing the number of vehicles crossing the site and the mean value of all the weigh and axle distance readings is calculated and stored at the corresponding tables. The summaries are also separated by vehicle class.

- Data in the flow tables is accessed to generate indicators per day; these indicators are calculated and represent parameters used as quality criteria for quality checks in each day.
- Having the indicators ready, the system analyses each full month of records and calculates the quality criteria, checking if any of the sites in any month has violated the calculated limits. If there is a violation, the software creates a record in the alerts_per_month table, which stores data quality warnings. A warning is defined as one record of quality criteria violation. More than one alert can exist for the same site in the same month if it violated more than one criterion.

4.2 Features of DQM system

In order to support the automatic application of standard quality checks, the prototype of Data Quality Management System developed for DNIT's WIM network counts on other functionalities, such as automatic warnings for questionable data quality and generation of diagnosis executive reports. Statistical and practical criteria are used for warnings, allowing for further investigation with graphs and tables whenever needed by the user. Figure 7 shows a screenshot from the developed computer tool for automated WIM data quality management:

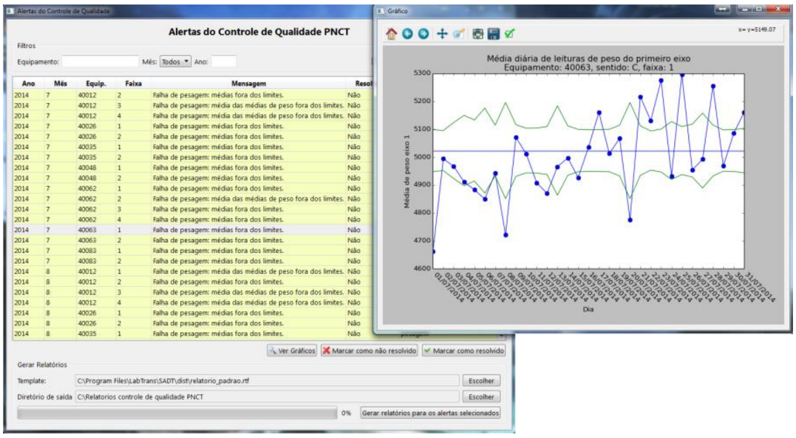

Figure 7 – Prototype computer tool

As shown on the screenshot, the tool generates a list of quality warnings immediately after the data is imported. These warnings may be directly accessed and visualized in the form of control charts, as shown on the right side of the image. From the warning list the user may also generate reports in editable format for comments and interaction with stakeholders.

5. Conclusions

- A prototype of a Data Quality Management System has been developed by DNIT and LabTrans for efficient quality control of measurement data from DNIT’s WIM network.
- A first set of quality criteria were identified based on international research and adapted to the Brazilian road traffic conditions based on data from the first operational PNCT sites.
- The selected quality criteria were converted to statistical control charts that were verified using a few months of data from a number of PNCT sites and the Araranguá test-site.
- The control charts were implemented in a prototype software tool for automated data quality management and remote monitoring of all sites in DNIT’s WIM network.
- The tool has shown potential for supporting the management of WIM network, improving the quality of the collected WIM data, and providing a guarantee for its applications;

- The next stage of the project include a large scale test operation of the prototype computer tool within all PNCT sites in order to fully assess the efficiency of the methodology and the computer tool in managing the quality of a large WIM network.
- In the test operation, further assessment and adjustments in the methodology for quality checks will be made as well as an evaluation of the implementation for a full production system.

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STUDY OF WIM SENSOR ELECTRO-MECHANICAL BEHAVIOR: A MODEL IN THE FREQUENCY DOMAIN

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Abstract
This article aims to propose a model of WIM piezoelectric sensor to help better understand the mechanical and electrical proprieties when installed on the road. The model consists in represent the sensor electric response using a tire load and the pavement deflection (response to the load effect), together representing the electromechanical behavior. Tests in laboratory and in the fatigue carousel test track are used to access the coefficients of the model. In laboratory, two types of test are design, one pure punching and another three-point bending test. The pure punching allows accessing the coefficient that correlates the effect of the force only. The three-point bending test allows accessing both coefficients. In the fatigue carrousel, the three types of sensors are tested with FWD and with a metallic plate over the sensors. The results presented in this article confirms some of the sensor electric characteristics, but also show new characteristics related to sensor position of the load and pavement response.

Keywords: Piezoelectric sensor, WIM sensors, WIM sensor electric mechanic model, Weigh-in-Motion, WIM, Pavement and sensor interaction, Pavement mechanic characteristics.

Resumo
Este artigo tem como objetivo propor um modelo de sensor piezoeléctrico WIM que permita melhorar a compreensão das propriedades mecânicas e elétricas quando instalados em rodovias. O modelo consiste em representar a resposta elétrica do sensor utilizando a carga de um pneu e a deflexão do pavimento. São utilizados testes em laboratório e na pista de testes do carrossel de fadiga para avaliar os coeficientes definidos pelo modelo. Em laboratório, dois tipos de testes são organizados, uma compressão direta e outra flexão-3-pontos. O teste de compressão direta permite avaliar diretamente o coeficiente que correlaciona o efeito isolado da caga sobre o sensor. O teste de flexão-3-pontos permite avaliar ambos os coeficientes. No carrossel de fadiga, todos os tipos de sensores são testados com o equipamento FWD e com uma placa metálica sobre os sensores. Os resultados apresentados neste artigo confirmam algumas características elétricas dos sensores, mas mostram também novas características relacionadas a posição da carga e da resposta do pavimento.

Palavra-chave: Sensores piezoeléctricos, sensores WIM, modelo eletromecânico de sensores WIM, Pesagem em movimento, WIM, Resposta sensor e pavimento, Características mecânicas de pavimentos.

1. Introduction

The weigh-in-motion (WIM) systems can have many applications, such as traffic counting, vehicle classification, axle load measurements, all kind of applications on traffic monitoring. WIM systems have been used for a while to data collection and pre-selection of over loaded trucks (COST-323, 1998). Today pavement managers have a demand for more accuracy. Thus, many research institutes are studying ways to improve data quality and system accuracy.

Many aspects can influence the WIM system accuracy, the quality of the sensors, the pavement behavior, temperature and the traffic and vehicle as they pass by the sensors zone (DNIT-UFSC, 2009a). In addition, the performance of any WIM system is dependent on road conditions, road geometry, and vehicle condition (DNIT-UFSC, 2009b). This paper specifically deals with the interaction between WIM sensors and the pavement response. Scheuter (1998) have study many factors affecting the WIM system accuracy. He established typical sensor accuracy and dependence on external factors such as intrinsic sensor error, longitudinal tilt, changing of position, pavement evenness, vehicle suspension, tire and speed.

To address these aspects, we first propose a numerical model that represents the WIM sensor electric response under the influence of an axle load and pavement deflection. Then we perform different laboratory tests to characterize the sensor behavior under different conditions of support and loading. The results are used to identify the model parameters.

Tests in the fatigue carrousel at IFSTTAR/Nantes with different ways of stimulation helped to studying the in-situ behavior in more realistic traffic condition. In parallel, the sensor model was implemented in to pavement design code to simulate sensor response taking into account the pavement deflection. Finally, we compare the theoretical results with the experimental ones.

This project is part of a cooperation between two institutions the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) and the Federal University of Santa Catarina (UFSC), by Transportation and Logistics Laboratory (LabTrans), in cooperation with the National Department of Transport Infrastructure (DNIT) of Brazil. The main goal for both countries is to use the WIM technologies to perform direct enforcement of overloaded vehicle on the main traffic stream. The development of this project was funded by the General Direction of Infrastructures, Transport and Sea (DGITM) within the frame of a research projects coordinated by IFSTTAR.

2. WIM sensors

The strip sensor with quartz technology are deliver as bars. The external part is an aluminum profile and inside there are several pastilles of quartz distributed separately from each other but connected by conductive element to the output. The internal form of the sensor allow only vertical effort to stimulate the internal pastilles. The ceramics sensor is generally made of powder ceramic compress inside of a metallic profile (some types are design as a tube). In the core there is a central core made of copper, which is connect to the output. The polymer strip sensor is composed by a polymeric film spiral-wrapped PolyVinyliDene Fluoride – PVDF inside of a copper flat tube. The optical sensor is design with a fiber optic inside of a dense foam. There are two known principles of measurement, one evaluates the decrease of optical transmittance. An optic-electronic interface detects the changes in the optical signal and transforms them into signals for traffic data processing. The strain gauge strip sensor uses strain gauges inside of a metallic profile, it transforms strain measurement into equivalent axle weight.

3. Electro mechanic general model proposition

By definition here, the WIM sensor is a piezoelectric bar. Supposing that the electrical charge (or tension on exit of the charge amplifier) produced all along the sensor is linear dependent of the force $f^*(s)$ apply on the surface (the load to measured) and the curvature $C^*(s)$ (related to the deflection of the pavement and of the beam). Following equation is produced.

$$Q^* = \int_0^l p^*(s) f^*(s) ds + \int_0^l r^*(s) C^*(s) ds \qquad (1)$$

where: Q^* is the complex amplitude of the output electrical charge measured, $f^*\,(s)$ and $C^*(s)$ are the complex amplitudes of the force the curvature along the sensor. $p^*\,(s)$ and $r^*(s)$ are two complex functions to be determined, which are eventually function of the frequency ω and the temperature θ.

In the expression (1), we consider electric charge produced as linear dependent on the all forces encountering the sensor contact with the pavement and the sensor curvature. Consequently, one formulation based on support reactions will have the same equivalent effect.

In laboratory test we use a punctual force applied at different points of the sensor surface, instead of distribute pressures. In the case of a one punctual force F* over the sensor applied at abscissa s0, we can write:

$$f^*(s) = F^* \delta(s^0) \qquad (2)$$
$$Q^*(s) = p^*(s^0) F^* + \int_0^l r^*(s) C^*(s) ds \qquad (3)$$

where $\delta(s^0)$ is Dirac distribution.

If we suppose r^* independent of s, from the relationship between deflection Y^* and curvature, $C^*(s) = \frac{\partial^2 Y^*}{\partial s^2}$, we can deduce the expression (4).

$$Q^* = p^*(s^0) F^* + r^* \left(\frac{\partial Y^*}{\partial s}(l) - \frac{\partial Y^*}{\partial s}(0) \right) \qquad (4)$$

The term $\Delta P^* = \frac{\partial Y^*}{\partial s}(l) - \frac{\partial Y^*}{\partial s}(0)$ represents the complex amplitude of the difference between slopes (algebraic) of the bar between its extremities.

To identify the functions p* and r* in laboratory, two testing modes can be used:

- One by pure punching with the sensor-bar put over an infinitely rigid support. In this case, the curvature C^* is equal to zero and the sensor electrical response depends uniquely of the force and the coefficient $p^*(s^0)$, which can then be directly measured:

$$Q^* = p^*(s^0) F^* \qquad (5)$$

- The other one by the three-point bending test, which make possible to identify both $p*$ (s^0) and r*, considering different support spans. Assuming a linear mechanical behavior of the bar, we can determine can determine the geometrical factor φ_i^*, for each span ($i = 1, 2, ...$) and given frequency, so that:

$$\frac{\partial Y_i^*}{\partial s}(l) - \frac{\partial Y_i^*}{\partial s}(0) = \varphi_i^* F^* \quad (6)$$

Applying into the equation (4) we have the equation (8).

$$Q_i^* = (p^*(s^0) + r^*\varphi_i^*)F_i^* \quad (7)$$

For $i > 2$, this system can be solved by the least square method. In the case of two equations only, we get:

$$p^* = \frac{1}{\varphi_1^* - \varphi_2^*}\left(-q_1^* \frac{Q_2^*}{F_2^*} + q_2^* \frac{Q_1^*}{F_1^*}\right) \quad (8)$$

$$r^* = \frac{1}{\varphi_2^* - \varphi_1^*}\left(\frac{Q_2^*}{F_2^*} - \frac{Q_1^*}{F_1^*}\right) \quad (9)$$

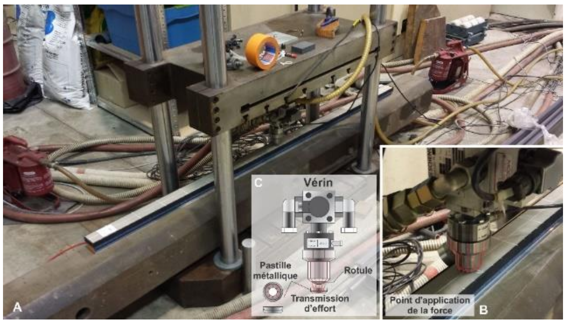
- One in pavement when the wheel is approaching the sensor without touching it, or making the wheels rolling over a little metal plate covering the sensor without contact with its surface. In these cases, the force F^* is equal to zero. The sensor electrical response depends uniquely of the curvature and the coefficient r^*.

$$Q^* = \int_0^l r^* C^*(s) ds \quad (10)$$

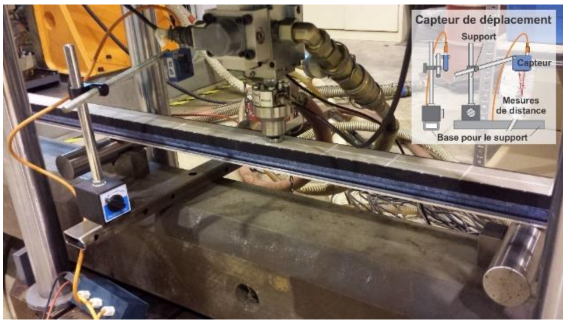
4. Laboratory tests

The piezoelectric quartz and ceramic sensors technologies are the only two tested in laboratory. The first one is a 1.75m quartz base sensor, which is rigid enough to be tested without any mounting support. The second is a 3.6m ceramic base sensor, which is not rigid enough and a mounting adaptation is needed.

Both p^* and r^* are determined in laboratory. Using a hydraulic press mounted in a metallic structure support. The sensor stays positioned under the contact piston. The press has a 7kN capacity, which can displace in the vertical plane. The maximum displacement speed is 2m/s and the maximum frequency of 1kHz. The contact of the piston is a spherical joint type, to ensure that the force is perpendicular to the sensor surface every time. In the punching test, the sensor stays over an unreformed metallic bar (see (A) in Figure 1). In the three-point bending test the sensor stays over two cylindrical supports and the piston stays at central position, with respects to the two supports (see (B) in Figure 1).



(A)



(B)

Figure 1 – In (A) details of the punching test, in (B) the details of the three-point bending test

4.1 Punching test

During the punching test with the Quartz sensor, a sinusoidal force is applied on the sensor (5, 10 and 20Hz) with amplitude of 3kN. A pre-charge of 0,5kN maintains the contact between the piston and the sensor surface. Temperature is constant and around of 25°C. The force signal, sensor electrical response, piston displacement and external displacement sensor are recorded. The punching test is done in each sensor during the manufacturing process. The results here can be compared to the sensor calibration sensitivity from the manufacturer.

69 measurements total are performed at each 2.5cm over the sensor surface. Variation of sensitivity along the sensor is identify. The sensor electrical response confirm that the sensor is constitutes by small pastilles space every 5 cm. For a distributed force, like a pneumatic, several pastilles are stimulate reducing dispersion of a single point solicitation. Figure 2 show the moving average for different frequencies (5, 10 and 20Hz), also show that the sensor response has a frequency dependence. Over all frequencies, the maximum sensitivity was 1.75 and response dispersion over all measurements of 1.7%. The sensitivity variation along the sensor length means that for a high accuracy WIM system, the tire position must be taken into account.

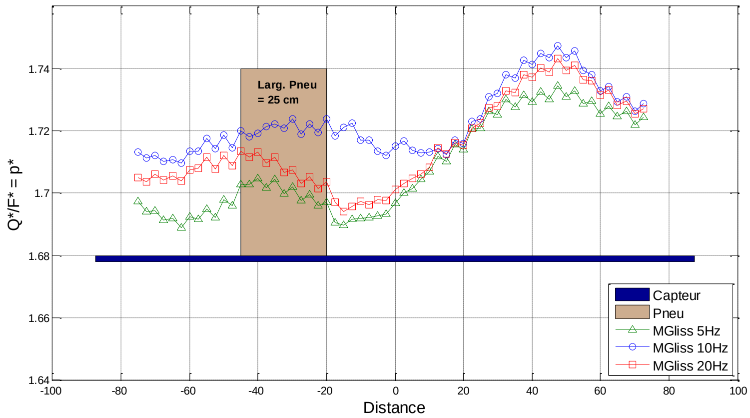
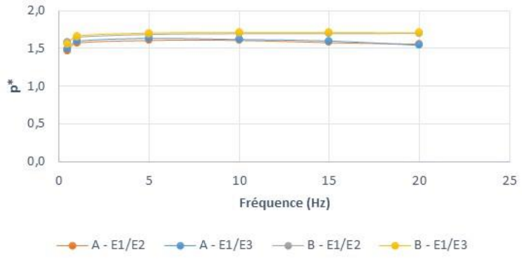


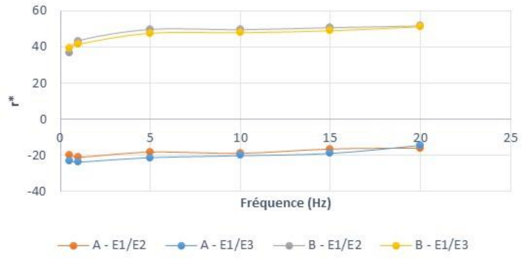
Figure 2 – Moving average of the electrical response at different positions for different frequencies

4.2 Three-point bending test

In the three-point bending test, the piston stays in the center of the two supports. A sinusoidal force is applied in several frequencies are tested between 0.5 and 25Hz. Temperature remained at 25°C. Three supports span was chosen (E1 = 77, E2 = 57cm and E3 = 57cm, displacing the sensor in 15cm). Sensor was positioned in normal position (Face A) and inverse (Face B). Figure 3 shows the values of p^* (A) and r^* (B) calculated for each test frequency. The difference on the sensor response, between the normal position and inverse, is represented by the difference of sign on the values of r^*.



(A)



(B)

Figure 3 – In (A) the values for p* and in (B) values of r*, calculated for the modalities E1 and E2 (Face A and B) and E1 and E3 (Face A and B).

To determine how important p^* and r^* are to the sensor electrical response, we assume a real situation. Under a load of 65kN, the deflection of a typical structure of the national road network in France generally is below of 0.40mm with a radius of curvature at the top of the order of 2000m. In these conditions, the curvature of the pavement surface is 1/2000 under the load and it gets smaller far from the center of solicitation. Supposing the curvature of 1/2000m constant in the expression (3), conducts to overestimate the part related to the curvature. The sensor in normal position (Face A) have $p^* = 1.6$ and $r^* = -18.1$. The sensor electrical response can be assumed.

$$Q^* = 1.6 \times F^* - \int_0^l 18.1 \times C^*(s)\, ds \qquad (11)$$

The part that represents the curvature $C^*(s)$ along in the sensor length of 1.75m is equal to: $18.1 \times \int_0^l C^*(s)\, ds = 18.1 \times \int_0^{1.75} \frac{1}{2000} ds = 18.1 \times 0.000875 = 0.016$.

The part that represents the force F^* for 65kN is equal to: $1.6 \times 65 = 103.5$.

The total electrical response is: $Q^* = 103.5 - 0.016 = 103.516$.

The response is 99.98% related to the superficial stress and 0.02% to the curvature. In the case of inverse curvature, the sensor response still would be below of 0.02%. This represents that the response part related to the sensor curvature can be neglected.

5. In-situ tests

The fatigue carousel test track is a circular track. It has a circumference of 120m at the radius of 19m. The in-situ tests main proposal is to stimulate the sensors in two different conditions: one pure bending without the load direct over the sensor, and another, conjugating the bending and the load action over the sensor. The metal plate and FDW equipment (see Figure 4 (A) and (B) respectively), placed over the WIM sensors, can reproduce these two conditions.

(A) (B)

Figure 4 – The image (A) shows the metal plate covering one sensor, the plate details and alignment with sensor, in the image (B) show the FWD trailer positions relatively to the sensor

5.1 Quartz sensor

Figure 5 compare the two signals from the acquisition of the quartz sensor. The graphic above presents the two signals, the response of the sensor in normal condition (without the metal plate) and in blue, the sensor response covered with the plate (deflection only). The week signal intensity, the graphic bellow presents a zoom at the ordinates axle. The relation between maximal amplitudes is less than 0.3%. The deflection sensitivity of this sensor on deflection is neglected compared with the sensitivity founded to test punching solicitation.

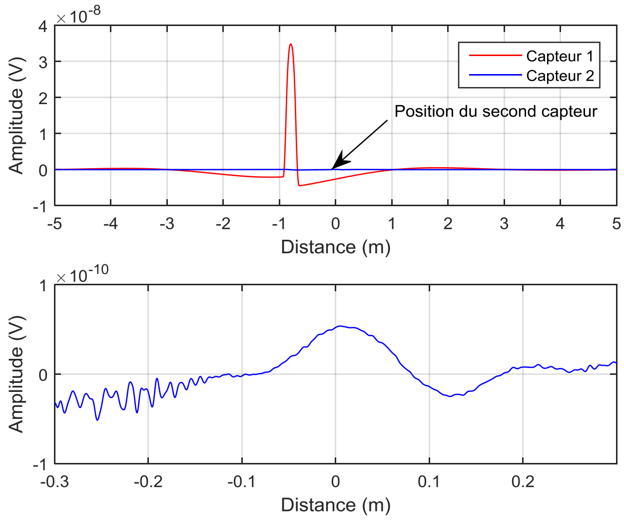


Figure 5 – Comparison of the piezoelectric quartz sensor response, in blue the presence of the plate (flexion only) and in red the sensor in normal condition (flexion and punching)

Figure 6 shows the comparison of the same sensor responding to the solicitation of the equipment. In red is the FWD plate over the sensor, in blue the plate beside the sensor top surface. Comparing the two sensors maximal amplitudes is less than 0.2%, showing once more that the sensor sensitivity to deflection only can be neglected.

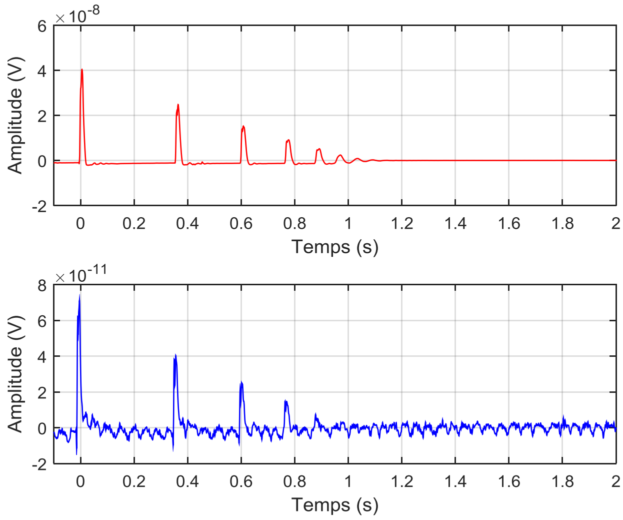


Figure 6 – Comparison between sensor response in the FWD test, above is the sensor response with the FWD plate over the sensor, below, in blue, is the sensor response with the FWD plate just beside the sensor surface

5.2 Ceramic sensor

Figure 7 present the same signal comparison in the test with the metal plate covering the piezo ceramic sensor and the normal situation. In this situation, the signal scale in the ordinates is about 3.33. The signal observed in the presence of the metal plate cannot be neglected. It represents up to 25% of the measure level. The pavement stiffness, consequently its deflection, will generate an influence over the measure level for this lows speed test (about 1 rpm).

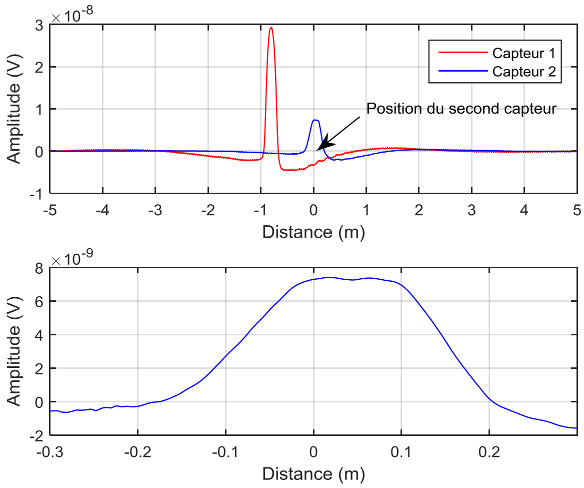


Figure 7 – Comparison of the piezoelectric ceramic sensor response, in blue the presence of the plate (flexion only) and in red the sensor in normal condition (flexion and punching)

The two signal acquired of the same sensor (ceramic technology), presented in Figure 8 above, the first FDW impact and the subsequent chocks. The graphic below corresponds to the signal when the FWD plate beside the sensor top surface. The scale of ordinate axle is adapted in each case. In the second case, it corresponds an amplification factor of 15. The maximal amplitude relation, difference maximal value and the minimal, is approximately 10%. The pavement deflection sensitivity can be not neglected and is estimated less than 10%. No doubt that this sensitivity is superior, because de maximal deflection measured at 30 cm away from the load represent approximately 65% of the maximal deflection under the load.

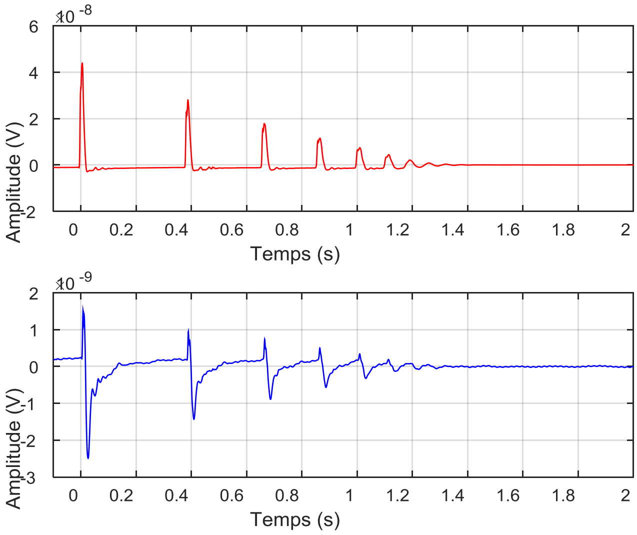


Figure 8 – Comparison between sensor response in the FWD test, above is the sensor response with the FWD plate over the sensor, below, in blue, is the sensor response with the FWD plate just beside the sensor surface

6. Conclusions

The piezo quartz sensor, during the punching test, show that the sensors sensitivity varies according to the load position across the sensor surface. This sensitivity variation is estimated as 1.75%, which is close to the characteristics provide by the manufacturer (< 3%). In other words, knowing the position of the tire associated to the sensor calibration at this point is the way to reduce some of the uncertainty. The results obtained shows for the punctual charge a variation of sensitivity along the sensor approximately of 2.91%. The punctual test allows reaching directly the p^* value, the mean value of the sensitivity of p^* is 1.72pC/N.

The same sensor in the three-point bending shows independence of the mechanical behavior flowing the sensor orientation (normal or inverted). Differently, the electrical response is dependent of the sensor orientation, which means to conjugate the precedent conclusion where the curvature is negative or positive he sensor response may be different due to deflexion effects. The test puts in evidence the electrical response sensitive to low frequency solicitation, but is constant by 5 Hz. In real situation, the vehicle speed is much higher to this frequency. The estimated sensitivity p^*, at normal position (face A), is about 1.60pC/N. Different from the sensitivity coefficient deduced by the punching test, by 7%, resulted because of the different configuration between the two types of test.

The in-situ test confirms the sensor behavior observed in laboratory tests, both technology. The results indicate that the sensitivity of the quartz due flection can be neglected if compared with the punching effect in normal condition of measurement.

The ceramic sensor response recorded shows the strong sensitivity to deflection, which represents about 10 up to 30% of the maximal level of measurements. The signal processing should take into account this strong influence. To improve the ceramic sensor signal, a complex modeling of the pavement and sensor it is necessary with rigorous laboratory characteristics of the electro mechanic parameters.

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MODELING TANK VEHICLE WEIGH-IN-MOTION SYSTEM

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Abstract

Weigh-in-motion (WIM) systems are used to monitor axle forces from heavy vehicles on bridges and roadways. For application in law enforcement it is necessary to consider the accuracy of the measurements and the overload tolerance of the system. The national traffic regulations stipulate the Gross Vehicle Weight (GVW) and the vehicle axle load limits for each type of road. The sloshing effect of liquids in tank vehicles during measurements with WIM systems on the weight control is an issue. This paper presents a model simulating forces exerted on the ground by the axles of a tank vehicle carrying liquid during weigh-in-motion. Computational multi-mass-spring models and laboratory experiments were developed to show the acceleration influences in axle forces, considering one vehicle with six axles and two types of tanks: with baffles (internal partitions) and without baffles, in the reduce prototype.

Keywords: Modeling, Tank vehicle, Heavy Vehicles, Weigh-in-Motion, WIM.

Resumo

Os sistemas de pesgem em movimento são utilizados para o monitoramento da força por eixos de veículos de carga em pontes e rodovias. Em aplicações de fiscalização de peso é necessário considerar a exatidão e a tolerância de sobrecarga. O conselho nacional de transito estipula os limites de peso totais e por eixo dos veículos. A questão é a possibilidade de deslocamento do liquido durante a fiscalização do peso de veículos tanque nos sistemas de pesagem em movimento. Este trabalho apresenta a simulação da força exercida por eixos de veículos tanque transportando liquidos durante a pesagem de veículos em movimento. Um modelo computacional massa-mola-amortecedor e experimentos em laboratório foram desenvolvidos para mostrar a influência da aceleração na força por eixos, considerando um veículo de seis eixos em dois tanques: um com quebra ondas e outro sem quebra ondas, em modelo reduzido.

Palavras chave: modelagem, veículos tanque, veículos de carga. pesagem em movimento, WIM.

1 Introduction

The use of WIM systems to monitor the Gross Vehicle Weight (GVW) in roadways is usual. It is already in use in Brazil since 1980 in order to enforce application of the regulation. Nevertheless their application suffers from metrological issues (Inmetro. 375/2013) prohibiting their use for tank vehicles carrying liquid (Inmetro. 403/2013). There are questions about the accuracy of the measurements considering the sloshing effect that may be present in the tank itself. It is necessary to consider the limits of tolerances and uncertainties before a penalty due the overload (Contran 489/2014) (Contran 258/2014) can be applied. Some studies present results of the WIM measurements, considering the application in law enforcement (Faruolo. 2011) (Faruolo and Martha. 2008) (Faruolo and Pinto. 2015) (Faruolo and Pinto. 2015 b) (Faruolo. 2015).

The force exerted by the axle on the pavement was object of diverse models. The software MATLAB/SIMULINK can be used to simulate the axle load of a truck (Canale et al. 2009). The dynamic amplification effect can be studied in field (Deng L and Cai C S 2011). Spring-mass-dampers represent the suspension of the vehicle (Belay. et al 2008), whereas a multi degree of freedom model is used for the truck (Gonzalez. et al 2010).

The tank sloshing effect was studied in different applications. Considering the Lagrangian iterations (Tsukamoto. et al 2011). In laboratory in 3D model of an experiment (Chin-Hua. et al 2013). In containers using a multi-mass-spring to characterize the imminent effect of sloshing on transport of liquids (Reyhanoglu and Hervas. 2012)

For the metrological aspect in case of the WIM application in legal processes it is important to consider the international recommendations of OIML (R134. 2016). But in general application is important consider the ASTM-1318 (2002) and COST (1997).

2 Methods and Results

The mathematical model for simulation of the transport of liquid in a tank vehicle is developed, considering also the elements from the experiment in Laboratory.

2.1 Experiment in Laboratory

An experimental prototype as a reduced scale model was developed using two acrylic tanks, one for a tank with baffles and other one for the case without baffles. Both tanks were installed in a six axis vehicle. The experimental vehicle is depicted in figure 1 and was used to get parameters for the computational models.

Figure 1 –vehicle prototype with tank without baffles.

The prototype uses a scaled platform with load cells simulating a WIM station to investigate the sloshing effect in this context. The motion of the vheicle starts near the platform and stops after all axles pass on the axle platform. The dymamic effect is investigated considering the velocities 0.1 m/s, 0.2m/s and 0.3 m/s with full tank and with 75% of its capacity. The results are present in table 1. The average of the dynamic effect are 1.20, 1.25 and 1.25, represents that the GVW apparently increases by a factor about 20% at velocities up to 0.3 m/s.

Table 1 - Simulation results in laboratory

Type of tank	Load capacity	0.1 m/s	0.2 m/s	0.3 m/s
Tank without baffles	75%	1.15	1.22	1.23
	100%	1.20	1.21	1.17
Tank with baffles	75%	1.23	1.28	1.31
	100%	1.24	1.28	1.30
Average		1.2	1.25	1.25

2.2 Mathematical model

The model of a tank vehicle carrying liquid is developed for the study of the WIM system. This model simulates the axle forces applied at the pavement considering the dynamic effect. A system of nineteen degrees of freedom, second order, nonlinear differential equations is established in equation 1.

$$\overline{M}\ddot{q}(t) + \overline{C}\dot{q}(t) + Kq(t) = F(t) \tag{1}$$

Two simulations were made, one to simulate the tank vehicle with 3l, corresponding to 75% of its full capacity, and other model with 4l, the fully filled tank. In the table the sum of the axle force and the relative error considering the weight are presented. In the figures each axle force in different simulations are presented.

The simulations for the tank without baffles with 75% of the capacity are presented at table 2 considering a constant velocity at 5 m/s, 1.38 m/s and stacionary, and axle forces are represented at figure 2. Table 3 and figure 3 shows the results for simulations in different constant forward pushing forces of 4N, 5N and 12N for same tanks and capacities.

Table 2 - Axle load in constant velocity for the tank without baffles in 75% of the capacity

	v=5	v=1.38	v=0
Axle sum	75.74600059 N	75.640422 N	75.53799 N
GVW	7.721304851 kgf	7.7105425 kgf	7.700101 kgf
Error %	0.276686372	0.1369153	0.001316
Reference	7.7kgf	7.7kgf	7.7kgf

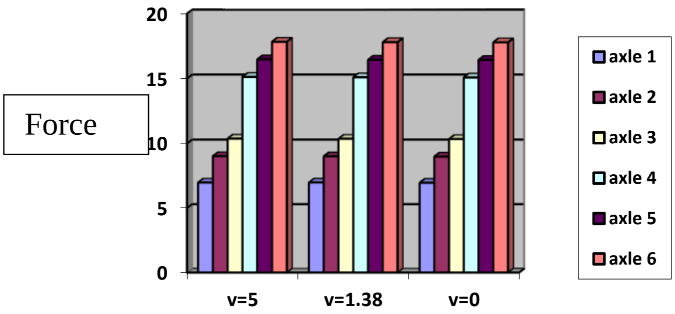

Figure 2 – Axle load in velocity 5 m/s, 1.38 m/s and 0 for the tank without capacity 75%

Table 3 - Axle load in constant force for the tank without baffles 75% of the capacity

	F=4 N	F=5 N	F=12 N
Axle sum	75.53701299N	75.537013N	75.537N
GVW	7.700001324 kgf	7.7000013 kgf	7.7 kgf
Error %	1.71995E-05	1.724E-05	1.06E-08
Reference	7.7kgf	7.7kgf	7.7kgf

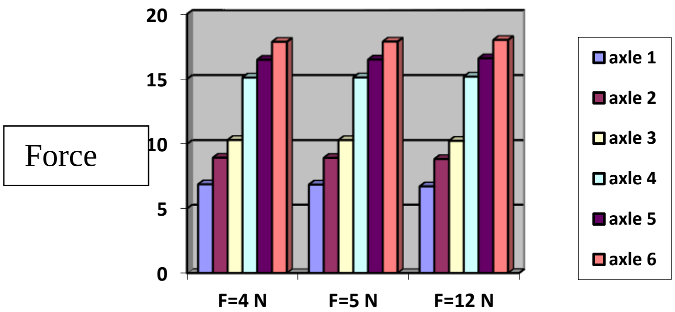

Figure 3 – Axle load constant force 4N 6N and 12 N for the tank without baffles 75% of the capacity

The simulations for the tank with baffles in 75% of the capacity are presented at the table 4 and figure 4 show the axle force for constant velocity, and the results for constant force are present at table 5 and figure 5.

Table 4 - Axle load in constant velocity for the tank with baffles 75% of the capacity

	v=0 m/s	v=1.38 m/s	v=5 m/s
Axle sum	82.48824N	82.48824N	82.48824N
GVW	8.408587 kgf	8.408587 kgf	8.408587 kgf
Error %	0.102226	0.102226	0.102226
Reference	8.4 kgf	8.4 kgf	8.4 kgf

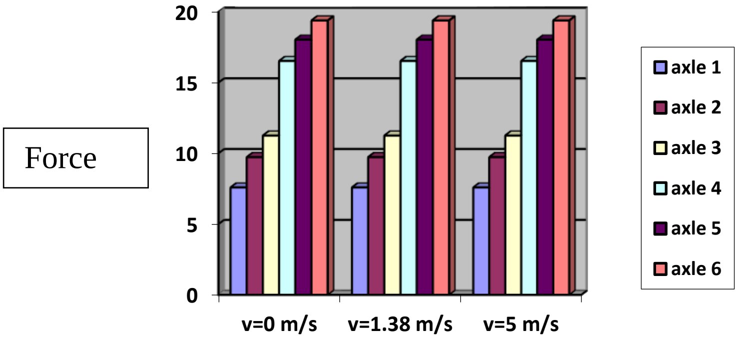

Figure 4 – axle loads in constant velocity 0, 5 m/s and 1.38 m/s tank with baffles capacity 75%

Considering the tank without baffles in 100% of the capacty, the full tank, the axle force results in velocity constant are present in table 6 and figure 6, and for constant force are in table 7 and figure 7. Considering the tank with baffes in the same capacity the simuating results are presented in velocity constant in table 8 and figure 8, and in force constant in table 9 and figure 9.

Table 5 - Axle load in constant force for the tank with baffles 75% of the capacity

	F=4 N	F=5 N	F=12 N
Axle sum	82.61001N	82.64046N	82.85356N
GVW	8.421kgf	8.424104kgf	8.445827 kgf
Error %	0.250004	0.286948N	0.545556
Reference	8.4 kgf	8.4 kgf	8.4 kgf

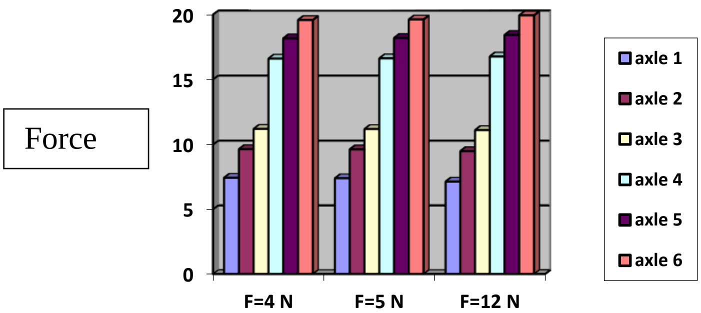

Figure 5 – Axle load constant force 4N, 5N and 12 N for the tank with baffles capacity75%.

Table 6 - Axle load in constant velocity for the tank without baffles capacity 100%

	v=5	v=1.38	v=0
Axle sum	85.36456N	85.36456N	85.36456N
GVW	8.70179 kgf	8.70179 kgf	8.70179 kgf
Error %	0.020571	0.020571	0.020571
Reference	8.7 kgf	8.7 kgf	8.7 kgf

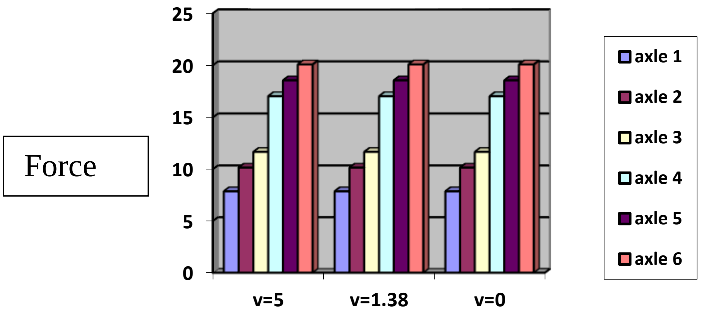

Figure 6 – Axle load in velocity 5m/s, 1.38 m/s and 0 for the tank without baffles capacity 100%

Table 7 - Axle load in constant force for the tank without baffles in capacity 100%.

	F=4 N	F=5 N	F=12 N
Axle sum	85.39665N	85.40467N	85.46082N
GVW	8.705061 kgf	8.705878N	8.711603N
Error %	0.058169	0.067568	0.133363N
Reference	8.7 kgf	8.7 kgf	8.7 kgf

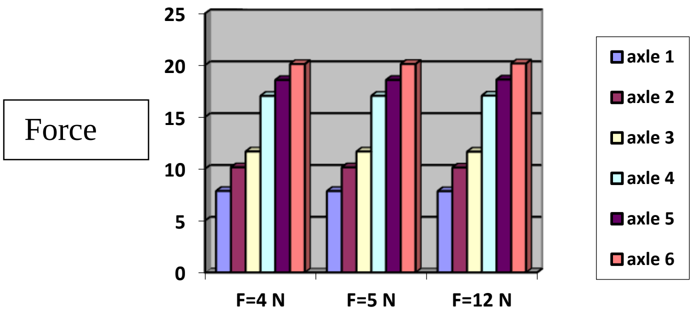

Figure 7 – Axle load constant force 4N, 5N and 12 N for the tank without baffles capacity 100%.

Table 8 - Axle load in constant velocity for the tank with baffles capacity 100%.

	v=5 m/s	v=1.38m/s	v=0
Axle sum	92.23805N	92.23805N	92.23805N
GVW	9.402452 kgf	9.402452 kgf	9.402452N
Error %	0.026082	0.026082	0.026082
Reference	9.4 kgf	9.4 kgf	9.4 kgf

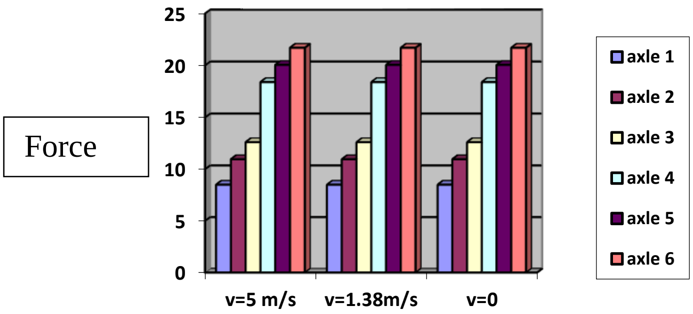

Figure 8 – Axle load in velocity 5 m/s and 1.38 m/s for the tank with baffles capacity 100%.

Table 9 – axle load tank with baffles constant force capacity 100%.

	F=4 N	F=5N	F=12N
Axle sum	92.23781N	92.23774N	92.23731N
GVW	9.402427 kgf	9.40242 kgf	9.402376 kgf
Error %	0.025816	0.025749	0.02528
Reference	9.4 kgf	9.4 kgf	9.4 kgf

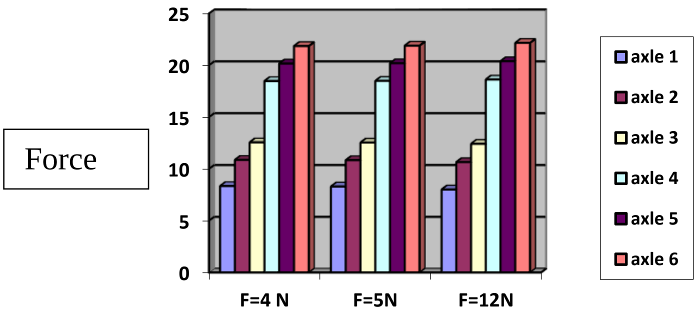

Figure 9 – Axle load constant force 4N, 5Nand 12 N for the tank with baffles capacity 100%.

The results presented show that there are a little influence at the GVW measurement in case of the force and velocity constant present only in table 2, 5 and 7.

3 Discussion

The laboratory experiment is designed as a scaled model of the vehicle. Nevertheless, the influence of the fluid motion does not obey the same geometrical scaling. In order to properly take into account its characteristics specific relations between viscosity and density of real and scaled fluids must be kept. Since different fluids could be transported in tank vehicles this aspect is not considered in this article and water is used in the experiments for simplicity. Also considering a linear scale of 1:20 volume of the tank, fluid, and inertia forces are correspondingly cubic scaled. Main purpose of the experiment is to verify the mathematical modeling.

The reference for the dynamic measurement presented in laboratory considers one GVW measurement in a static scale. In dynamical measurements there are some difficulties for the assessment of axle loads, specially in a tank vehicle. The motion of the liquid load influences the accuracy of these measurements.

The WIM system also presents other influences rather than the velocity alone. There is a physical limit of the dimension between the platform and the wheels of the vehicle. Different wheels at different sides of the axle can pass in different instants of time during load measurements. There is an impact factor in the load sensor, related to the road surface and also to the dynamic behavior of the load cell itself. The transient dynamic effect of the vehicle suspension dynamics, excited by the transition from rod to load cell and back to the road, influences in the measurement. All these factors are expressed in the dynamic factor obtained in the experiments. Although not all of them being directly caused by the velocity all of them relate to the motion of the vehicle in some way, therefore to the velocity. In a static measurement they would not be at hand.

The vehicle starts the movement near the load sensor and stops almost immediately after the measurements were made. In the computer model the vehicle was considered in constant acceleration during up to 30s. Therefore in the laboratory experiments the inertial influence of the liquid load is more important.

Considering all effects presented at the dynamic measurement of the force, sum of the axles loads of the vehicle, the value is increased about 20% of the reference value adopted for the mass of the vehicle. This difference can be considered a systematic increment, due to the dynamic measurement, and be used in order to propose parameters for improving their accuracy. It is interesting to keep the velocity constant to simplify the definition of these parameters.

4 Conclusion

The experiment shows the dynamic effects which are related to velocity. Considering tanks without baffles, in the case of being filled to full capacity, dynamic effect is lower than at other conditions. The dynamic effect varies from 1.15 up to 1.31 in the condition considered that the vheicle starts the motion near the axle load sensors and stops just after all axles passed.

The model demonstrates that considering the full tank the constant velocity and constant force do not influence significantly in the WIM system for the determination of GVW. However, for the tank without baffles, with a constant force initiating its motion, there are some variations at axle forces in the case of 75% tank capacity. For the tank with baffles there is greater variation of axle loads in this condition. The maximum error is 0.54% of GVW for the tank without baffles considering the constant force of 12N and filled to 75% of its capacity.

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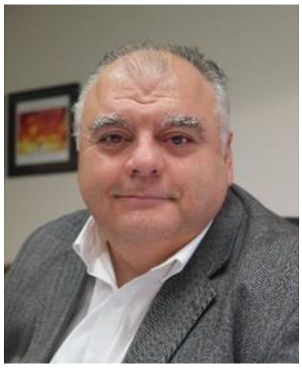
ACCURACY OF MASS SENSOR UNITS (MSUs) USED FOR ON-BOARD MASS (OBM) MONITORING





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Abstract

In Australia, On-Board Mass (OBM) systems are applied to measure and record the mass of heavy vehicles in conjunction with the Intelligent Access Program (IAP), using a combination of telematics technologies and mass sensor units (MSUs) fitted to the vehicles' axles. With both the mass and location of enrolled vehicles monitored for compliance with access arrangements, Road Managers obtain stronger assurances that the conditions of access are being met. For Transport Operators, better access in exchange for monitoring offers productivity, efficiency and environmental outcomes – greater loads, fewer trips and greenhouse gas emissions, and more direct routes. In order to ensure the accuracy of data, MSUs are periodically calibrated. This paper presents a statistical analysis of calibration data derived MSUs used in the OBM program. It examines the accuracy and the impact of calibration in an operational environment in which OBM monitoring is progressing towards regulatory purposes, and presents a methodology that can be used in similar analyses.

Keywords: On Board Mass Monitoring, In-vehicle technology, Mass Sensor Units, Compliance.

Résumé

En Australie, le pesage embarqué (OBM) est appliqué pour mesurer et enregistrer les masses de poids lourds dans le cadre du programme d'accès intelligent (IAP), en utilisant une combinaison de technologies de télématique et de capteurs de masses (MSU) installés sur les essieux des poids lourds. Avec la masse et la localisation des véhicules participant à ce programme, les gestionnaires routiers ont une probabilité plus grande que les conditions d'accès soient réunies. Pour les opérateurs routiers, ceci résulte en des accès simplifiés en échange d'une amélioration de la productivité, de l'efficacité et des résultats environnementaux : charges plus grandes, trajets inférieurs, émissions inférieures, itinéraires plus directs. Pour assurer une bonne précision des données, ces MSU sont calibrés périodiquement. Ce papier présente une analyse statistique des données de calibration des MSU utilisés dans le programme OBM. Il traite de la précision des données et de l'impact de la calibration dans un environnement opérationnel où cette surveillance se dirige de plus en plus vers du contrôle des charges.

Mots-clés: Capteurs embarqués, technologie embarquée, capteurs de masse, respect de la règlementation.

1. Background

To participate in the OBM monitoring program, vehicles must be enrolled in the Intelligent Access Program (IAP), the first land-based voluntary, regulatory telematics program in Australia, which began operations in 2009. The IAP uses the Global Navigation Satellite System (GNSS) to monitor heavy vehicles' road use. There are three parameters which are currently monitored in the IAP: position, time and speed. The current use of OBM monitoring with the IAP is transitional in nature, intended to bridge the gap between the IAP and a more advanced program that integrates mass directly with the IAP.[1] It supports a limited number of vehicles (approximately 200) and is designed to monitor specific vehicle combinations travelling on selected parts of the road network. The program has been operational since 2011, and following the delivery of operational learnings – including those related to accuracy of MSUs – Road Managers are looking to expand their use of OBM monitoring.

The goal is to progress to a more comprehensive monitoring program where OBM data collected can be used for regulatory and evidentiary purposes. This paper presents the statistical analysis of MSU accuracy, performed as a step towards an integrated IAP-OBM program. The analysis examines the accuracy of OBM systems and their ability to sustain the required accuracy of 2% with a confidence interval of 95% for Total Combination Mass. Itexamines the impact, including the frequency of calibration, and identification of malfunctions and possible tampering, that can impact the the accuracy in the real world operational environment.

2. OBM systems and OBM data

An OBM system determines both the Axle Group Mass (AGM) and Total Combination Mass (TCM) of a heavy vehicle, and includes the following key components:

- Electronic Control Unit (ECU) – installed in the rigid vehicle or prime mover, responsible for generating OBM data from the mass data collected from the Mass Sensor Units.
- User Interface (UI) – the screen and touchpad/keypad used by drivers to access and enter information
- One or more Mass Sensor Unit (MSU) – the load sensor and associated cables and connectors that measure the mass of an axle group.

Three types of MSUs are typically used with OBM systems: load cell sensors, air pressure sensors and strain gauge sensors.

Static data is currently the most reliable OBM data.[2] To ensure accuracy of these readings, OBM systems are calibrated every six months at weighbridges, where a calibration certificate is completed. The calibration certificate captures the OBM system's pre-calibration readings of individual AGM as recorded by the MSU and the corresponding readings recorded by the weighbridge. To complete the calibration, the OBM system is adjusted to match the MSU readings with those of the weighbridge as much as possible.

[1] Mass compliance, via OBM monitoring was considered as a first-day parameter of the IAP during the development phase, but was identified as in need of further trialing (Austroads 2003).
[2] Testing of OBM systems against a weighbridge at full load showed accuracies within approximately ± 500kgs or ± 2% of weighbridge for TCM (TCA 2009).

OBM data is generated automatically by the OBM system every 30 seconds (dynamic data) when the vehicle ignition is on. OBM data is also triggered when the driver requests it of the OBM system, when the vehicle is stationary (static data). Dynamic data can assist with the identification of malfunctions and/or indicate possible tampering(with the OBM system or the load of the vehicle).

In the process of delivering the next stage of OBM, the frequency of dynamic data may change to be captured at a higher frequency to enable better identification of malfunctions and/or possible tampering.

3. Importance of calibration and calibration requirements

The level of accuracy of MSUs or OBM systems also depends on the operational environment including the calibration frequency and procedure, and the ruggedness of vehicle route. Calibration guarantees that the margin of difference in measurements between the weighbridge and the MSUs approaches zero as much as possible, so that the calibration error margin does not compound long-term inaccuracies. For the purpose of this paper, analysis has been performed exclusively on air pressure transducers, those predominantly used in the OBM monitoring program.

The calibration procedure is performed under the following conditions:

- Calibration is performed for each required axle group
- A vehicle must be calibrated at EMPTY and FULL load conditions
- The EMPTY and FULL load conditions are measured by the same weighbridge
- The vehicle component(s) being calibrated must be on flat ground
- The entire vehicle combination is stationary
- The fuel tank(s) are at least 75% full
- The vehicle brakes are off
- Relevant wheels are not chocked
- The vehicle engine is running
- The ride height valves are in the correct positions
- Steer axle tyres are straight and parallel to the weighbridge
- Calibration at FULL load condition must reflect at least 75% of the maximum specified load per axle group
- Calibration at FULL load condition must not exceed the maximum specified load per axle group.

4. Importance of initial calibration

Experiments were conducted to determine if a calibration should be conducted just after initial installation of MSUs and OBM systems.

375 MSUs were tested soon after installation and their measurements were compared against the true values for fully laden states. After initial screening for completeness, 338 of 375 pre-

calibration records were used for further analysis, the results of which are in Table 1 and Figure 1.

Table 1: Pre-calibration statistics – fully laden

	Fully laden statistics for MSUs pre-calibration records taken before an initial calibration
Mean, %	-0.10
Standard deviation, %	4.2
Standard error, %	0.20
Skewness	-2.1
Minimum difference, %	-25.9
Maximum difference, %	14.9
Number of measurements	338

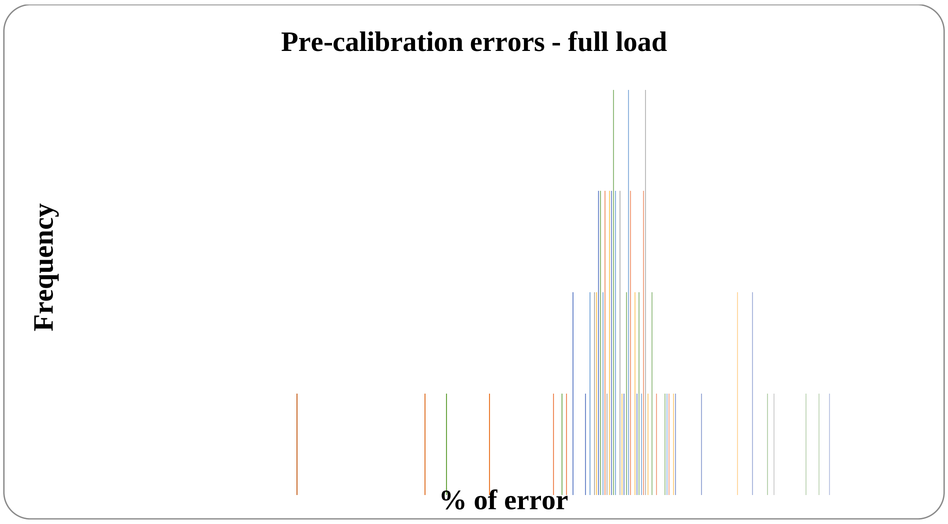

Figure 1: Error distribution graph for pre-calibration records taken before an initial calibration – fully laden

Figure 1 indicates a wide range of errors before MSUs are first calibrated, and the obvious non-normal distribution of errors. This strongly suggests the importance of the initial calibration as soon as possible, to ensure that values are sitting within the prescribed limits. Several peaks suggest the complex nature of inaccuracies when several factors might be involved, similar to the six month recalibrations discussed below.

5. Accuracy of MSUs in six months after an initial calibration

To analyse the accuracy of MSUs six months after initial calibration, data from calibration certificates, which are completed at weighbridges, was used. The 471 calibration records presented in these certificates included both the records taken at initial installation and subsequent re-calibrations after a six month period of field operation:

- Initial installation: The OBM system must be calibrated within one week after installation. Records were taken before the initial calibration was conducted to check the importance of the initial calibration (hereafter, pre-calibration records).
- After first calibration, OBM systems were re-calibrated six months later (hereafter, re-calibration records).

Only re-calibration records will be explored here. Figure 2 represents the error distribution graph for MSU re-calibration records.

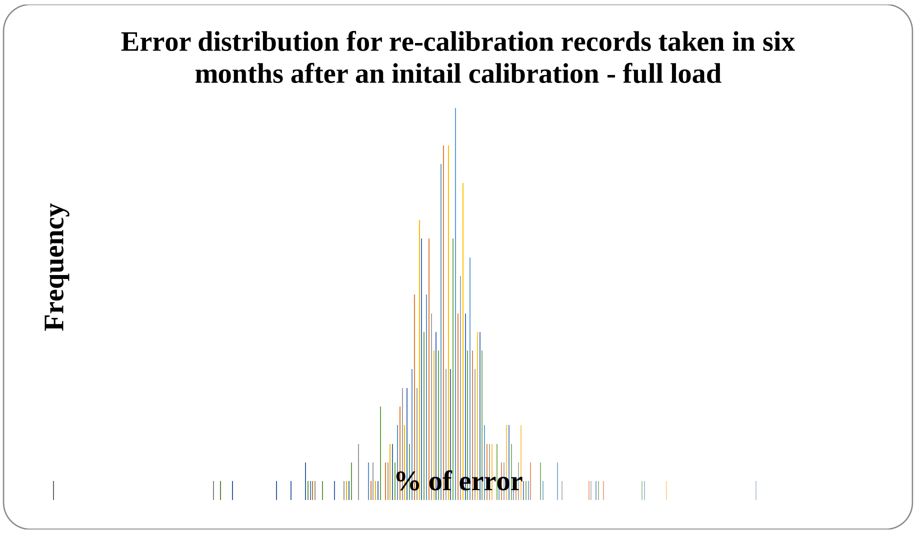

Figure 2: Error distribution graph for re-calibration records – fully laden

The Anderson – Darling Test was conducted to confirm the error distribution abnormality, and showed that the distribution was not normal. The statistical analysis derived is shown in Table 2.

Table 2: Re-calibration statistics for MSUs in six months

	Fully laden statistics for MSU re-calibration records
Mean, %	-0.10
Standard deviation, %	2.25
Standard error, %	0.10
Skewness	0.52
Minimum difference, %	-16.29
Maximum difference, %	12.73
Number of measurements	471

Relatively high values of the standard deviation, maximum and minimum differences, and failing the Anderson–Darling Test, suggest that simple rules of normal distribution should not be applied to the results. Therefore, two further tasks are explored below:

- Removal of outliers based on proven statistical methodologies and further data analysis
- Working with data as is to derive the accuracy values of MSUs.

6. Statistical removal of outliers and further data analysis using clean data

Statistical methodologies of removing outliers are not always accurate and can remove legitimate datasets. Caution should be taken when analysing such datasets and the nature of outliers should be considered. The outliers identified via statistical analysis are considered as missing data, and the remaining data will be used for the assessment.

This does not mean however, that the analysis should simply ignore the outliers. They must be reported in any statistical analysis to ensure they are accounted for, legitimately eliminated and understood in terms of how many are present in the dataset.

The statistical techniques of the Tukey method were applied in order to determine which values were possible outliers and subsequently remove them from further assessment.[3]Thirty potential outliers were found and eliminated, leaving 441 of 471 records further analysis.

Further analysis was conducted to group the MSUs to calculate how many were sitting within particular accuracy intervals. Table 3 below represents the number of measurements for fully laden sitting within particular accuracy intervals, while clear outliers are statistically eliminated.

Table 3: Number of MSU measurements within certain accuracies with outliers removed – fully laden

Total number of measurements without outliers	441
Number of measurements within 5%	441
Number of measurements within 4%	441
Number of measurements within 3%	422
Number of measurements within 2%	380

Even after potential outliers were removed, it cannot be said with total confidence that in six months all MSUs maintain an accuracy of 2% . Using Table 3, it is possible to statistically calculate the confidence intervals when MSUs would meet particular accuracy levels. This calculation would give an indication of the optimal accuracy value we can rely upon.

Before moving forward, a brief introduction is needed about the confidence level, confidence interval and adjusted Wald methodology used for making further assessment.

The confidence interval (ie. margin of error) consists of a range of values (interval) that act as good estimates of the unknown population parameter; and it is very rare that none of these values may cover the value of the parameter. For example, if a confidence interval of 2% is used and 97% of measurements meet a particular result, it is possible to be "sure" that if measurements are conducted for the entire vehicle fleet, all results would be between 95% (97%-2%) and 99% (97%+2%). Certain factors may affect the confidence interval, including size of sample, level of confidence, etc. and a larger sample size will normally lead to a better estimate. For a 95%-99.9% confidence interval, “reasonable boundary” means a 5% chance of not containing the measurement pass rates after many repeated tests.

The confidence level tells us how sure we can be. It is expressed as a percentage and represents how often the true percentage of measurement results lies within the confidence interval e.g. a confidence level of 95% means that one can be 95% certain.

[3] The Tukey method applies an algorithm of determination of various interquartile ranges, subsequent determination of the “reasonable” data ranges and elimination of outliers based on a particular algorithm using interquartile values and “reasonable” data range.

Calculating confidence intervals for particular values of confidence level will give a fair idea of how accurate MSUs might be, if calibrated within certain timeframes. To calculate the confidence intervals at particular confidence levels, the Adjusted Wald method was used, providing practical results for real world applications, particularly for situations when the number of measurements is too low or belong to a binomial distribution. This calculation was conducted for 95% and 90% confidence levels, shown in Tables 4 and 5.

Table 4: Confidence intervals for particular accuracy levels of MSUs for 95% confidence level – outliers statistically removed

	Confidence interval low level	Confidence interval high level	Best estimate
441 out of 441 are within 5%	99.17%	100%	99.77%
441 out of 441 are within 4%	99.17%	100%	99.77%
422 out of 441 are within 3%	93.35%	97.39%	95.48%
380 out of 441 are within 2%	82.59%	89.25%	86.00%

This result has a very significant implication when considering the performance of MSUs six months after their initial calibration: With the 95% confidence level we can state that, on average, six months after initial calibration, the MSU's accuracy meets the requirement of 4% and the measurement results are compliant with the accuracy requirements before the next calibration within 95.17% - 100% confidence interval.

Important practical conclusions can be derived from the Table 4. The confidence interval should sit between the values of 95% and 100%. This would mean that during the whole timing interval before the next calibration we can rely on at least 95% of MSUs in terms of their accuracy and integrity of measurements. Therefore, based on 471 measurements and 30 outliers statistically removed, it is possible to be 95% certain that the accuracy of MSUs in six months on average might sit at approximately 4% (or 5% adopting a conservative view). This is because the values of 3% and 2% accuracy give lower confidence intervals when, for example, only between 82.59% and 89.25% of MSUs can be relied upon before the next calibration. Remembering that with 30 outliers statistically removed to conduct an assessment, an accuracy between 4% and 5% is a more plausible conclusion.

However, some important comments should be made here about this conclusion:

- Additional work is required to determine how OBM systems (in particular the Mass Sensor Units) behave if calibration is conducted more often than every six months. Due to the time interval, it is unknown what may cause the errors such as malfunctions and tampering.
- Certainty is required to determine why the number of outliers is so high and how many MSUs were faulty/tampered with before the next calibration. This would help to determine how many measurements should not be taken into consideration.

Table 5: Confidence intervals for particular accuracy levels of MSUs for 90% confidence level – outliers statistically removed

	Confidence interval low level	Confidence interval high level	Best estimate
441 out of 441 are within 5%	99.32%	100%	99.77%
441 out of 441 are within 4%	99.32%	100%	99.77%
422 out of 441 are within 3%	93.74%	97.16%	95.48%
380 out of 441 are within 2%	83.17%	88.80%	88.00%

This result in Table 5 has some significant implications when we consider the performance of MSUs six months after their initial calibration:

With the 90% confidence level we can state that, on average, six months after initial calibration, the MSU's accuracy meets the requirement of 4% and the measurement results are compliant with the accuracy requirements before the next calibration within 99.32% - 100% confidence interval.

There are important implications which can be derived from the Table 5. Usually, it is good practice to have a confidence interval sitting between the values of 95% and 100%, i.e. between 95% and 100% of MSUs are trusted until the next calibration occurs. Therefore, based on 471 measurements, and 30 outliers statistically removed, it is possible to be 90% certain that the accuracy of OBM sensors in six months might be 4% (or 5% adopting a conservative view). This is because the values of 3% and 2% accuracy give much lower confidence intervals.

A very important implication also relates to the selection of confidence level. From Table 4 and Table 5 it is clear that the results for good confidence intervals, i.e. when values are around 95% or higher, do not differ too much for 95% and 90% confidence levels. Therefore, it is better to use a higher 95% confidence level which provides more assurance than 90% confidence level.

7. Working with the data as is without the removal of outliers

The removal of outliers based on proven statistical techniques without knowing the cause of their existence may not be legitimate, particularly when the number of outliers is relatively high. Therefore, analysis was conducted to determine MSU accuracy estimates with a full set of data, shown in Table 6. This analysis was also based on the Adjusted Wald method when outliers were essentially included as results sitting outside the specified accuracy requirements.

Table 6: Confidence intervals for particular accuracy levels of MSUs for 95% confidence level – whole data set

	Confidence interval low level	Confidence interval high level	Best estimate
441 out of 471 are within 5%	91.03%	95.66%	93.44%
441 out of 471 are within	91.03%	95.66%	93.44%

4%			
422 out of 471 are within 3%	86.48%	92.20%	89.43%
380 out of 471 are within 2%	76.82%	84.15%	80.55%

It is clear from Table 6 that there is no need to conduct calculations for 90% confidence levels as the results would be poor. It is clear that for the whole data set with outliers included, the accuracy of MSUs might be lower than 5% for almost 9% of MSUs, taking into account the confidence interval low level of 91.03%. The truth may sit somewhere in between conclusions derived from Tables 4 and 6. Therefore, it might be fair to say that:

- It is possible that some outliers represented in the data are related to faulty MSUs, unexpected wear and tear, tampering, human error, etc.
- More research is required with lower calibration intervals rather than with six months only
- Automatic data recording at weighbridges might be required to eliminate deliberate or unintentional errors
- Assuming legitimate statistical elimination of outliers, it is possible to say that, on average, 4% accuracy of MSUs might be feasible six months after their initial installation, based on 95% confidence level
- Assuming statistical elimination of outliers removed some legitimate data, because removal was based on statistical theory, it might be feasible that on average 5% accuracy of MSUs might be achieved in six months. This feasibility, however, is based on 95% confidence level and an acceptance that statistically up to 9% of the MSUs would be out of calibration before the next calibration
- At un-laden state, accuracies of static mass measurements for MSUs may be worse than 4% with 95% confidence level because of non-linearity of the error, which might reach up to 0.6%.

8. Accuracy of OBM equipment for Total Combination Mass (TCM) six months after an initial calibration

TCM readings were recorded just before the calibration conducted six months after the initial installation of OBM systems. These records represent re-calibration records.
After removing data containing incomplete calibration records, 140 vehicles were assessed for their accuracy compared against the reference weighbridge for fully laden only, shown in Table 7. The distribution error graph is shown in Figure 3.

Table 7: TCM Re-calibration statistics for vehicles – fully laden

	Fully laden statistics for vehicles re-calibration records taken before six months calibration
Mean, %	-0.1
Standard deviation, %	1.48
Standard error, %	0.1
Skewness	-0.01
Minimum difference, %	-8.41
Maximum difference, %	8.19
Number of measurements	140

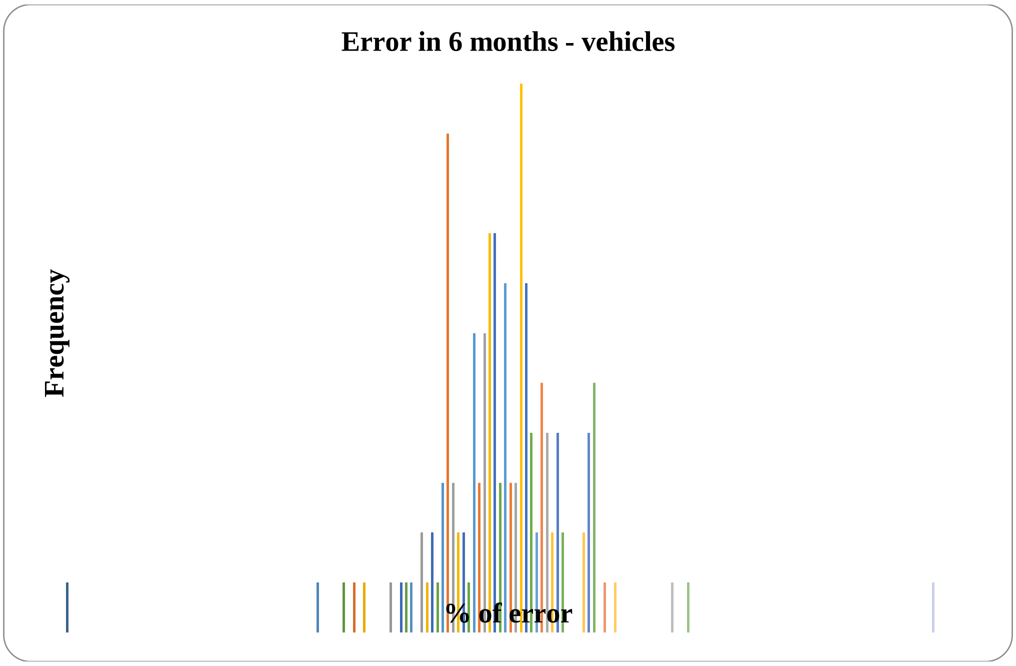

Figure 3: Error distribution graph for TCM re-calibration records taken in six months after an initial calibration – fully laden

Again, it is clear that the distribution is not normal. If all measurements are taken into consideration, the following appears to be the compliant data for different compliance criteria

Total records	140
within 5%	138
within 4%	138
within 3%	134
within 2%	130

Based on the Adjusted Wald statistical methodology we can calculate the confidence intervals for 95% confidence level, shown in Table 8.

Table 8: Confidence intervals for particular accuracy levels of TCM for 95% confidence level – the whole data set

	Confidence interval low level	Confidence interval high level	Best estimate
138 out of 140 are within 5%	94.93%	99.83%	97.88%
138 out of 140 are within 4%	94.93%	99.83%	97.88%
134 out of 140 are within 3%	90.91%	98.41%	95.07%
130 out of 140 are within 2%	87.26%	96.52%	92.25%

These results have some very significant implications when considering the performance of OBM systems consisting of individual MSUs in six months after their initial calibration. The result might be interpreted as follows:

With the 95% confidence level we can state that, on average, six months after initial calibration, the OBM system meets the accuracy requirement of 4% and the measurement results are compliant to the accuracy requirements before the next calibration within 94.93% - 99.8% confidence interval.
or
With the 95% confidence level we can state that, on average, six months after initial calibration, the OBM system meets the accuracy requirement of 2% and the measurement results are compliant to the accuracy requirements before the next calibration within 87.26% - 97.52% confidence interval.

Effectively, this means that up to 13%, of OBM systems might be out of calibration in six months if the accuracy requirement is 2%. This also means that if the accuracy requirement for the OBM system is 4%, the six month calibration interval might be more appropriate and the majority of systems will come to the next calibration still within the accuracy range. Specifically, in this instance, statistically more than 95% of systems would maintain required accuracy with only adjustments made at calibration to minimise the differences between MSUs and weighbridge measurements. It is important to stress that before the next calibration, the majority of systems shall be within calibration limits, otherwise systems might be running outside the prescribed accuracy before they are calibrated at some point.

Looking at the TCM data, it is also possible to say that several measurements might be outliers, caused by a faulty (rather than inaccurate) MSU, or incorrectly conduced or recorded measurements.

The Tukey method determined seven suspected outliers, which may improve the statistics in Table 8 dramatically, leading to a conclusion that the OBM system as whole meets the requirement of 2% in six months. However, while removing outliers might be a good practice for individual measurements like MSU measurements for axle groups, outliers for the whole OBM system are much less likely to occur. This is because the system consists of many individual MSUs and an outlier for one MSU causes a certain but not high shift in accuracy for the whole OBM system. As a result, it is recommended that the data from Table 8 be used to derive conclusions for TCM.

Therefore, based on Table 7 statistics, it is recommended to stay with at least 4% accuracy for the whole OBM system, with a six month calibration interval. Lowering calibration intervals may improve the accuracy but additional research needs to be conducted to prove the values.

9. Conclusions

There are a number of conclusions that can be made regarding accuracies of OBM systems based on this statistical analysis and findings from the operational environment:

- To ensure that values sit within the prescribed limits, it important to calibrate MSUs after installation.
- When the OBM system has been calibrated and is operating correctly, it is accurate to within 2% with a 95% confidence. As the OBM system operates in the real world, the accuracy is impacted by a number of factors – some known such as general operating impacts from the road environment and others unknown due to the lack of monitoring of possible tampering and malfunctions.

- For legal purposes such as direct enforcement of legal weight limits, at the current stage of research, it is difficult to guarantee the static accuracy of MSUs is better than 4% (with 95% confidence interval) even after the statistical removal of outliers. The frequency of calibrations as well as the lack of monitoring for malfunctions and tampering makes this difficult
- Statistical removal of outliers for MSUs may have errors in the approach as it uses statistical methodologies only without knowing the nature of outliers
- Even with a decent sample size of more than 100 measurements, the error distribution may not represent a normal distribution, including when outliers are statistically removed. This may mean that multiple factors contributing to the errors might be present with different coefficients of their influence

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Session 4 : Assessment of WIM Systems by Testing

Chair: Javier Jorge (NIIT, Argentina)

EVALUATION OF WEIGH IN MOTION SENSORS ON THE IFSTTAR ACCELERATED TESTING FACILITY





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Abstract
This paper presents an experiment, performed on the IFSTTAR circular accelerated testing facility, to evaluate the performance of different weigh- in-motion (WIM) sensors. A total of 10 WIM sensors were installed in a bituminous pavement. The response of the sensors was evaluated under a wide variety of loading conditions (different loading speeds, temperatures and lateral positions of the wheels). Different load types (single-wheel, dual- wheels, tandem, tridem) were also used. A large database, of about 30000 WIM signals, was collected. The full scale tests have provided the opportunity to evaluate the repeatability of the different sensors and the influence of different loading conditions (temperature, load type, loading speed). Recommendations for correcting and improving WIM sensor response have been made.
Keywords: Accelerated testing, weight in motion, piezo-electric sensors, metrological evaluation.

Résumé
Cet article présente une expérience conduite sur le manège de fatigue de l'IFSTTAR pour évaluer les performances de différents capteurs de pesage en marche (WIM). Dix capteurs ont été intégrés dans une chaussée bitumineuse épaisse. Leur réponse a été évaluée dans diverses conditions (vitesse, température, position latérale). Différents types de charges (jumelage, tandem tridem) ont aussi été testés. Une base de données de près de 30000 signaux a été constituée. L'expérience a permis d'évaluer la répétabilité des différents capteurs et l'influence des conditions de chargement (température type de charge, vitesse). Des recommandations pour la correction des mesures et l'amélioration du pesage en marche ont été formulées.
Mots-clés: Chargement accéléré, pesage en marche, capteur, capteur piezo-électrique, évaluation métrologique.

1. Introduction

Weigh-in-motion (WIM) technologies are used in several countries for screening overloaded heavy vehicles. Such systems are used for several purposes, including screening and preselecting overloaded vehicles for enforcement operations. However, these high speed (HS-) WIM systems are not yet approved by the legal metrology (OIML R134, 2006) for automated overload control and direct enforcement. The French project named "CSA surcharges" (Direct enforcement of overloads) was launched to address this objective (Cottineau et al. 2016). This project is organized into 5 tasks, among them, task 2 includes tests on the accelerated pavement testing facility of IFSTTAR in Nantes, France. This paper presents the results obtained during this experiment.

The pavement fatigue carousel of IFSTTAR is a circular accelerated testing facility where repeated loads in controlled conditions. This equipment is usually used to study damage of real pavements under accelerated heavy traffic. The full scale tests were used to evaluate the repeatability of 4 types of WIM sensors and the influence of loading conditions. Specifically temperature, load type, loading speed, and load position.

The fatigue machine has 4 loading arms which can apply loads up to 130 kN. Each arm can be equipped with different wheel configurations (single-wheel, dual-wheel, tandem or tridem). It can apply up to 1 million cycles per month at speeds from 7 km/h to 100 km/h. Loads can be applied at 11 predetermined positions on the transverse profile. The ring test road is 120m long and built by road construction companies using standard road work equipment.

2. Description of the Full Scale Experiment

2.1 Description of the Test Site

The pavement testing facility of IFSTTAR Nantes is a full scale facility, designed to study damage of real pavements, under accelerated heavy traffic (Figure 1). This equipment hasthe following features:

- a circular test track, 120 m long and 6 m wide;
- a maximum loading speed of 100 km/h;
- four loading arms, with a maximum load level of 130 kN on each arm (65 kN on a single wheel);

Only half of the track was used for the experiment, the other half being dedicated to another test. The experiment was carried out on a thick bituminous pavement consisting of a 7 cm thick asphalt concrete wearing course, over 34 cm of asphalt road base, resting on a granular subbase. The deflection level was about 100 µm, meeting the requirements of class 1 (Excellent site) of the European specifications for WIM by COST 323 (Jacob et al., 2002).

Ten WIM sensors, including four piezo-ceramic Thermocoax sensors, four piezo-quartz Kistler sensors (of two different types, F and G), and two piezo-polymer Meas-Spec sensors have been installed on the fatigue test track following the manufacurer’s recommendations. Table 1 summarises the characteristics of these different sensors. Figures 2 shows the sensor positions on the test track. In addition to the WIM sensors, the test track was also equipped with 4 temperature sensors placed at different depths in the pavement and 8 accelerometers installed on the 4 arms of the traffic simulator to monitor the dynamic load variations.

Figure 1 – The full scale pavement testing facility of IFSTTAR Nantes.

Table 1 – Characteristics of the evaluated WIM sensors

N°	Technology	Manufacturer	Type	Length (m)	Sensitivity (pC/N)
1	Quartz	Kistler	9195F421	1.75	1.752
2	Quartz	Kistler	9195F311	1.50	1.761
3	Ceramic	Thermocoax	VB FW CI1/3.6m/RG 58GT/45m	3.60	0.97
4	Ceramic	Thermocoax		3.60	0.97
5	Quartz	Kistler	9195GC41	1.75	1.569
6	Polymer	Meas-spec	Roadtrax BL	2.00	53
7	Quartz	Kistler	9195GC31	1.50	1.694
8	Polymer	Meas-spec	Roadtrax BL	2.00	61
9	Ceramic	Thermocoax	VB FW CI1/3.2m/RG 58GT/50m	3.20	0.97
10	Ceramic	Thermocoax		3.20	0.97

Three data acquisition systems have been used in parallel to record the different measurements: 2 ground based systems, and one on-board system installed on the traffic simulator, for the accelerometer measurements. To synchronize these 3 systems, four detection cells have been placed on the four arms of the traffic simulator, to measure precisely the time of passage of the loads on the WIM sensors.

2.2 Experiment Methodology

The experimental methodology included 3 phases:

1. a first phase where the 4 arms were equipped with single wheels, loaded at 45 kN.
2. a second phase, where the 4 arms were equipped with single wheels, with two different loads (45 kN and 55 kN) and different tire pressures (7, 8.5 and 9 bars).
3. a third phase, where each arm of the traffic simulator was equipped with a different wheel configuration: single-wheel loaded at 45 kN, dual-wheels loaded at 65 kN, tandem loaded at 90 kN, tridem loaded at 135 kN.

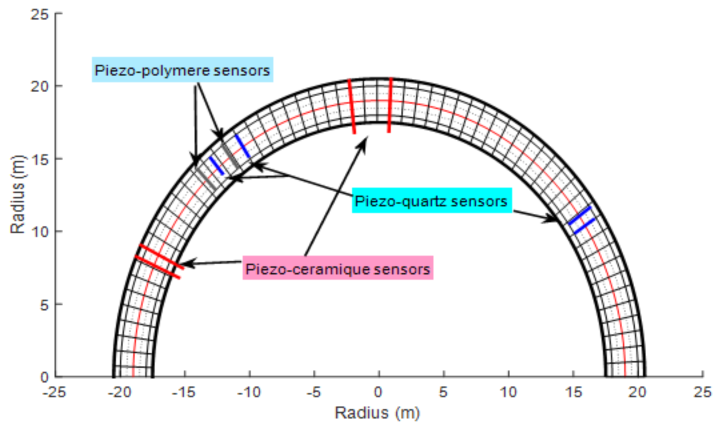

Figure 2 – Position of the WIM sensors on the fatigue test track

During each phase, various tests have been performed, to evaluate the influence of several parameters:

- the loading speed (30, 50 and 70 km/h)
- the transversal position of the wheels (11 positions, with a spacing of 10.5 cm)
- the pavement temperature, which was modified by running the tests at different hours of the day: early morning (23 to 27 °C) or in the afternoon (40-44 °C).

For technical reasons, the 70 km/h loading speed could not be applied during the third phase, with multiple wheels. All tests were conducted in one month (July 2014). The first analysis indicated a much higher variability of the signals obtained with the dual wheels, due to mechanical vibrations. Additional tests were performed in November, after solving the problem. All the measurements were stored in a database of more than 30,000 WIM sensor signals, corresponding to about 300 different measurement conditions.

3. Data Processing and Analysis

Data processing of the transducer signals included:

- Noise filtering, with a low pass filter (50 Hz) including a zero phase digital filtering.
- For the piezo-ceramic sensors, a high pass filtering (1Hz) with a zero phase digital filter;
- Integration of the polymer sensor signals, including a procedure which removes the linear trend of the signal to obtain a positive peak similar to that of the other sensors;
- Integration of the signals, over a time interval corresponding to the time of application of each wheel. The signal area thus obtained is proportional to the applied load. It is finally converted into a load value, using the coefficient of sensitivity of the transducer.

4. Response of the WIM Sensors

Examples of signals obtained with the different sensors are presented on figure 3. These measurements have been performed during the third loading phase, with the following conditions:

- Each arm of the carrousel was equipped with a different load, in this order: arm 1 - single wheel, 45 kN; arm2 - tandem with single wheels, 45 kN per wheel; arm 3 – dual wheels, 65 kN; arm 4 – tridem with single wheels loaded at 45 kN per wheel.
- Loading speed : 30 km/h.
- All wheels placed in lateral position n°1, corresponding to a radius of 18.47 m.

Figure 3 presents electrical signals obtained with the different types of sensors, for tridem wheels in the same conditions. Piezo-quartz and piezo-ceramic sensors are associated with a charge amplifier which integrates the analogic signal. The piezo-polymer sensors don't include a charge amplifier. A numerical integration has been applied. The shape of the signals are similar.

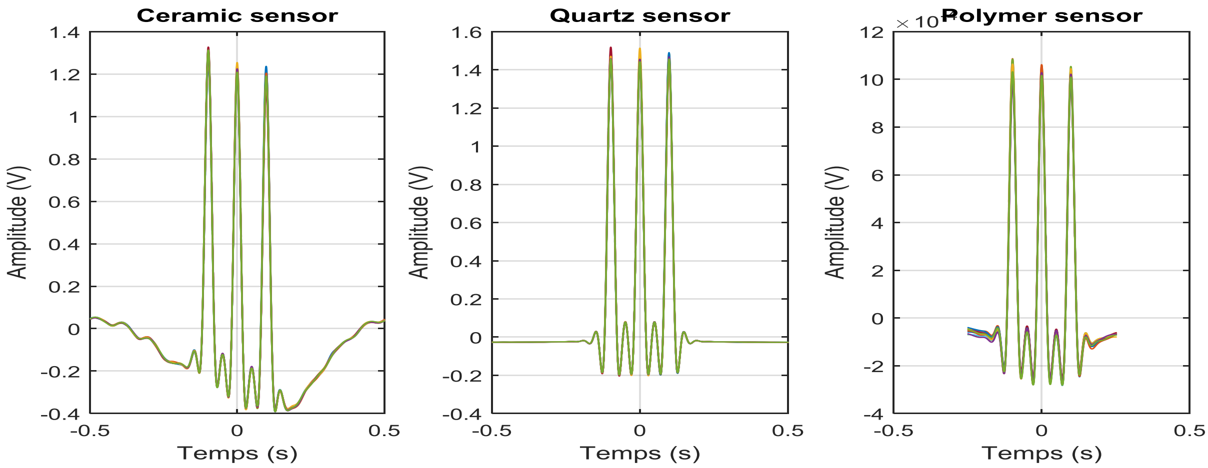

Figure 3. Examples of signals measured by the 3 types of transducers under tridem axles, (speed 50 km/, load position 6).

For the different sensors, the following observations can be made:

- The Kistler piezo-quartz sensors present the most accurate response. The signals present a low noise (somewhat higher for type G), and return very rapidly to zero after the application of each load. This means that the sensor is sensitive only to the vertical load.
- The piezo-polymer sensor presents a similar shape, but the measurement level is different from zero before and after the loads.
- The response of the piezo-ceramic sensor is also different. This sensor starts to respond before the first wheel passes on the transducer, and returns slowly to zero. This indicates that this transducer is sensitive to the pavement deformations.

5. Influence of Measurement Conditions

Figures 4 to 6 compare raw transducer signals recorded in different conditions, and illustrate the influence of 3 factors : loading speed, lateral load position, and temperature. All the signals presented have been recorded under the same single wheel, loaded at 45 kN.

Influence of loading speed

Figure 4 shows the influence of the loading speed on the piezo-quartz and piezo-ceramic sensors at a temperature of the wearing course of 42°C . Clearly, the length and amplitude of the signals depends on the loading speed.

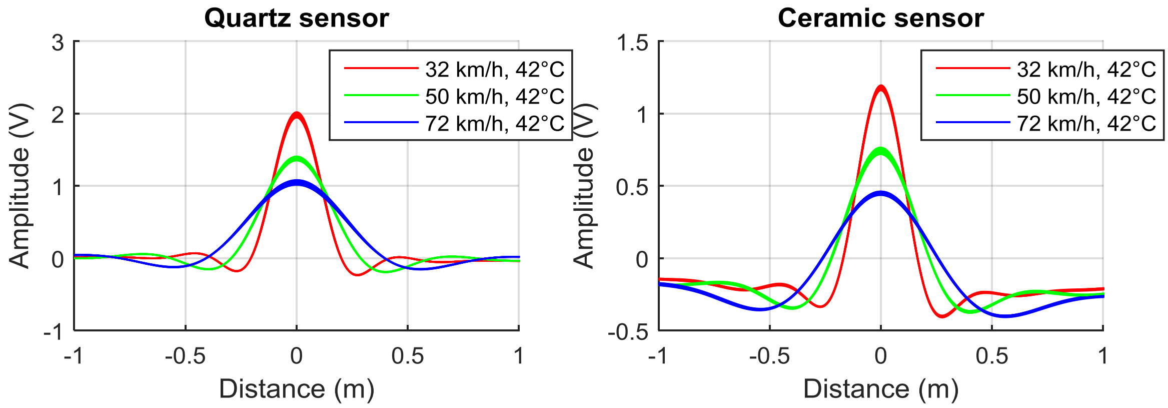

Figure 4 – Examples of response of the piezo-quartz and piezo-ceramic sensors at 3 different speeds, (single wheel , constant temperature).

Influence of lateral wheel position

Figure 5 illustrates the influence of the lateral position of the wheel on the measurements of the piezo-ceramic sensor. A difference of 50 cm in the lateral position leads to a significant change in the amplitude fo the signal. The results are similar for the other sensor types. The influence of the wheel position can be due to a variation in the sensitivity of the sensor, with the lateral positionand/or to dynamic loading effects (the road profile is not exactly the same at the two lateral positions). Clearly, an on site calibration procedure could be used to take into account and correct this effect of the lateral position.

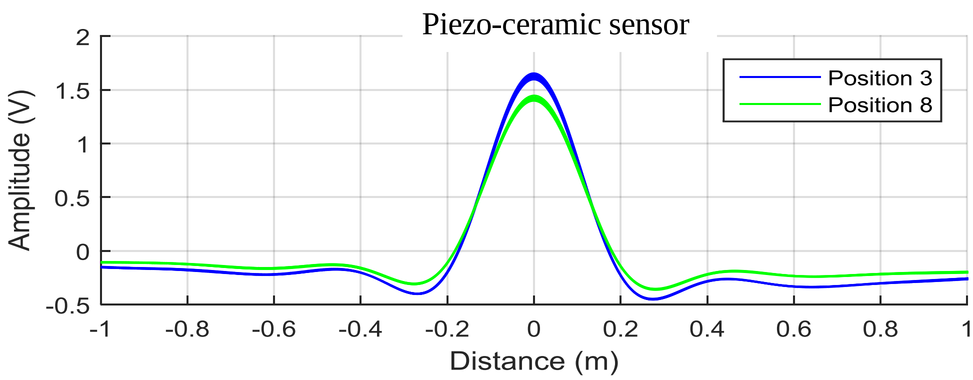

Figure 5 –Examples of signals of the piezo-ceramic sensor recorded at 2 different lateral positions (single wheel, constant speed and temperature)

Influence of temperature

Figure 6 compares signals obtained with the piezo quartz type G sensor,and the piezo-polymer sensor for a single wheel, passing at a speed of 50 km/h, in the central position, for two different temperatures, 24°C and 41°C. The response of the piezo-polymer sensor depends strongly on temperature. This is due to the thermal sensitivity of the polymer material composing the sensor. On the contrary, for the piezo-quartz sensor, the influence of temperature is not significant.

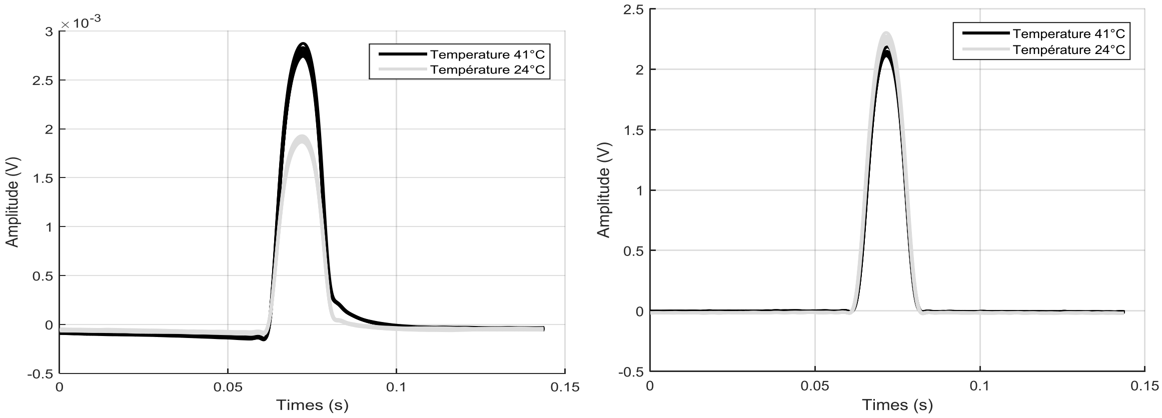

Figure 6. Example of measurements of a piezo-polymer sensor (left) and piezo-quartz type G sensor (right) at two temperatures : 24 °C and 41 °C. (single wheel, constant speed)

6. Repeatability of the Measurements and Influence Factors

6.1 Analysis of the Results

The indicator chosen for the comparison of the different measurements is the area under the sensor signal, calculated over a fixed length of 1.0 m, expressed in Volt.m. Figure 7 gives examples of calculated values of this “normalized” surface, obtained for a piezo-polymer sensor, for two temperatures, and 11 wheel positions, for a single wheel, and a constant speed. The results indicate:

- A good repeatability of the measurements for each position, at one temperature (10 measurements have been made for each position).
- A significant variation of the sensor response with the lateral position (as pointed out previously), which confirms that a position-dependent calibration factor will have to be determined.
- A strong influence of temperature on the polymer sensor measurements.

Figure 8 shows measurements obtained with a piezo quartz sensor (G series) under 2 different single wheels, with almost identical loads, for 11 lateral wheel positions (all other conditions being equal). The measured static loads were 4600 kN for load 1 and 4650 kN for load 2 , at position 6. The results show that:

- The difference between the measurement under the two loads is very similar for each position, and is significantly higher than the static load difference. It can probably be explained by a difference in the dynamic behavior of the 2 arms of the carousel.This shows that some dynamic effects exist on the carousel, and that measuring the dynamic load with one sensor is not sufficient to determine accurately the static load.
- The measurements of the piezo-quartz sensor are also dependent on the lateral position.

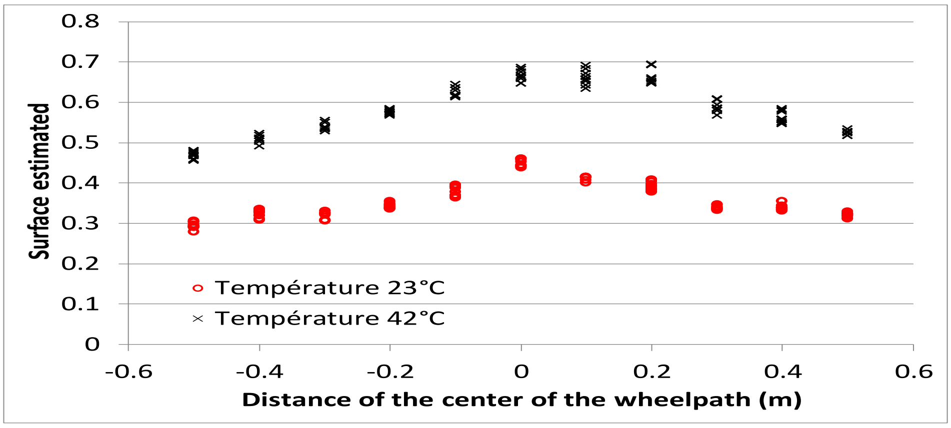

Figure 7 – Comparison of the measurements of a piezo-polymer sensor at 2 temperatures, for 11 lateral positions

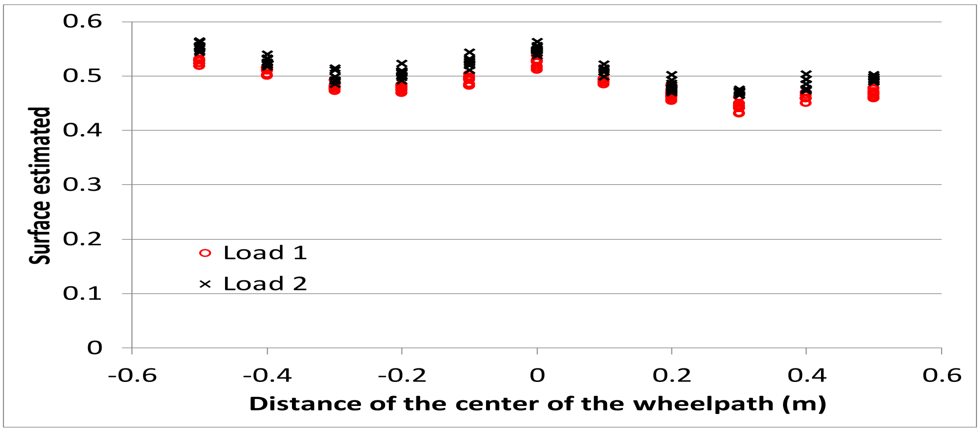

Figure 8 – Comparison of the measurements of a piezo-quartz sensor for 2 different wheel loads, and 11 lateral positions (all other conditions being identical)

6.2 Repeatability of the Measurements

The repeatability of the different measurements has been calculated for the different test conditions (position, temperature, speed). For each constant test condition, the repeatability has been evaluated by the coefficient of variation of the measurements. For each sensor, 1256 coefficients of variation have thus been calculated, including 1080 coefficients relative to a single wheel, and 88 coefficients relative to tandem or tridem axle loads. Table 2 summarizes the mean and maximum coefficients of variation obtained for the different loading conditions, for teach type of sensors.
For a single wheel, the repeatability of the piezo-quartz and piezo-ceramic sensors is always less than 3% with a mean value close to 1.5%. The repeatability of the polymer sensors can reach 4 %. For dual wheels, the repeatability of the different sensors is a little better (it decreases by 0.5 to 1 %). It is also better for multiple axles, than for a single wheel.

The repeatability of the piezo-ceramic and piezo-quartz sensors is similar, and better than for the polymer sensors. The repeatability of the polymer sensors seems insufficient to meet the OIML specifications.

Table 2 – Summary of the repeatability of the different sensors, for different loads (coefficients of variation, in %).

	Single wheel		Dual wheels		Tandem		Tridem	
	Max	Mean value	Max	Mean value	Max	Mean value	Max	Mean value
Quartz	3%	1.3%	1.7%	1%	2.1%	1.2%	1.5%	0.8%
Ceramic	2.5%	1.2%	1.6%	1%	2.%	1.1%	1.2%	0.8%
Polymer	4%	2.2%	2.3%	1.6%	3.9%	2%	2.4%	1.4%

6.3 Factors of influence

To summarize the results obtained for the 1256 different measurement conditions, Table 3 presents the maximum range of variation of the measurements induced by the variation of each influence factor (speed, temperature; wheel position), for each sensor type. This table shows that:

- Piezo-polymer sensors present the highest variability (35%) with the different influence factors, and are not suitable for accurate measurement of vehicle loads.
- Piezo-quartz sensors present the lowest variability, but present some sensitivity to temperature and wheel position.
- For piezo-ceramic sensors, the main factor of influence is the wheel position.

Table 3 – maximum variation of measurement level induced by the influence factors

	Speed	Temperature	Position	All Together
Quarz F	+/- 1%	+/- 4%	+/- 5 %	+/- 10 %
Ceramic	+/- 2%	+/- 1%	+/- 11%	+/- 15%
Quartz G	+/- 1%	+/- 4%	+/- 5%	+/- 10%
Polymer	+/- 10%	+/- 25%	+/- 16%	+/- 35%

6.4 Measurement Corrections

The previous results indicate that to measure vehicle weights accurately, WIM sensor measurements require some corrections. In this project, several correction methods have been evaluated, using only single wheel measurements. The most efficient correction was obtained using the following linear regression:

$$S_{cor} = S_{est}\big(a(pos) * V + b(pos) * T + c(pos)\big)$$

Where: *pos* is the transverse position of the wheel;

a,b,c are coefficients which depend on the transverse position

V is the speed of the wheel;

T is the temperature of the pavement at 3 cm depth;

S_{est} is the raw measurement (estimated surface of the sensor signal)

S_{cor} is the corrected measurement

Figure 9 shows the variations of the measurements obtained with the piezo quartz sensors, after correction, for different test conditions (temperature, speed, wheel position). The values have been normalized to 1. After correction, the maximum variation of the measurements is ±6% for the ceramic and quartz sensors and ±10 % for the polymer sensors.

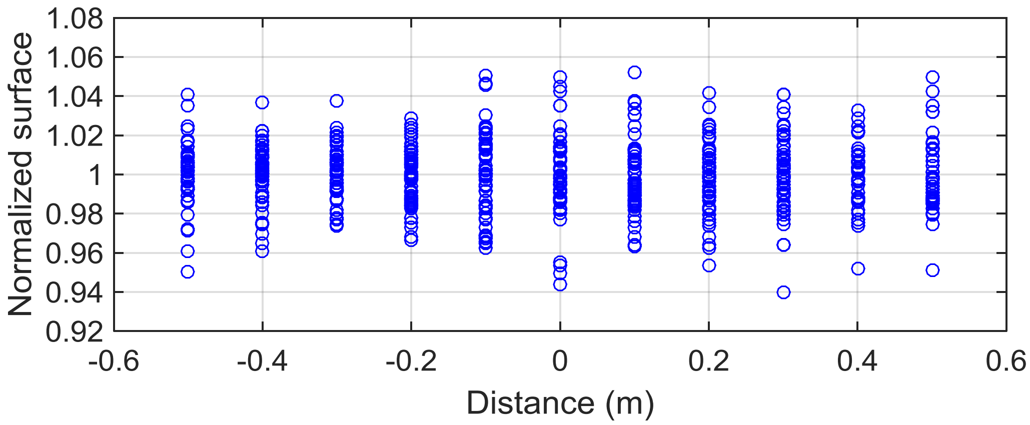

Figure 9 – Normalised measurements of the piezo-quartz sensors after correction (different positions speeds and temperatures)

7. Conclusion

The objective of this full scale experiment was to evaluate different types of WIM sensors in controlled conditions of temperature, speed and lateral position, that could nott be achieved on a road test site. The results indicated a good repeatability of the various sensors, of the order of 3% to 4 % percent. It also highlighted the influence of different parameters on the WIM results. The lateral position of the wheels can induce a variation of more than 5% of the measurements for all sensors. It is the main factor of influence for ceramic and quartz sensors.

A multifactorial linear interpolation, taking into account the wheel position, allowed reducing the measurement variability to ±10% for the piezo polymer sensors and to ±6% for the ceramic and quartz sensors which have been evaluated. Nevertheless, it will be necessary to develop suitable procedures for determining the correction coefficients on site, including:

- Calibration of the sensors according to lateral position, and determination of the correction equation;
- Measurement of the lateral position of the vehicles;
- Measurement of pavement temperature and vehicle speed;

8. Acknowledgements

The authors would like to express their thanks to the French Transport Ministry's DGITM Directorate and the CEREMA for their support of successive R&D projects on weigh- in - motion technology and to the WIM manufacturers, STERELA and FARECO, for their collaboration.

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HIGH-SPEED WEIGH-IN-MOTION ROAD TESTS IN FRANCE




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Abstract

The ongoing direct enforcement of overloads research project (Cottineau et al., 2016), supported by the French Ministry of Transports (DGITM), led by IFSTTAR and carried out with the Cerema, aims to demonstrate the feasibility of direct overload enforcement with adapted existing WIM technologies to be certified. The project contains a work package dedicated to on road testing of improved or adapted WIM systems and new filtering algorithms, to check the compliance with the specifications of direct enforcement. This work package is carried out in partnership with several WIM vendors. The road trial is conducted on a French motorway operated by the concessionary company SANEF in eastern France. The organization of the experiment, the systems and sensors tested, the test plans and the first results are presented. The first days of measurements in Autumn 2015 were devoted to calibrate the systems. The first measures show very promising and accurate results.

Keywords: Weigh-In-Motion, Overloads, Direct enforcement, WIM tests, WIM systems.

Résumé

Le projet « Contrôle Sanction Automatisé (CSA) des surcharges » (Cottineau et al., 2016), financé par le Ministère français en charge des transports, piloté par l'IFSTTAR et réalisé en partenariat avec le Cerema, a pour objectif de démontrer la faisabilité de l'utilisation d'un système de pesage en marche à vitesse courante pour le contrôle légal et automatisé des surcharges, et de sa certification. Le projet contient un volet d'étude dédié aux essais sur site de systèmes améliorés et adaptés avec de nouveaux algorithmes de tri, pour en vérifier la conformité vis-à-vis des exigences du CSA surcharges. Il et est réalisé en partenariat avec plusieurs fabricants de systèmes de pesage en marche. Les essais sont organisés sur une autoroute concédée à la société SANEF dans l'est de la France. L'organisation des essais, les différents systèmes et capteurs, le plan d'expérience et les premiers résultats sont présentés. Les premières journées de mesures à l'automne 2015 ont été dédiées à l'étalonnage des systèmes. Les premières mesures donnent des résultats très encourageants et relativement précis.

Mots-clés: Pesage en marche, surcharges, contrôle sanction autamatisé, essais et systèmes de pesage en marche.

1. Workpackage on the road trials and objectives

The French project "CSA surcharges" intends to study the feasibility of using high speed WIM system (HS-WIM) for direct enforcement of overloads and to prepare a certification procédure. The project is described in detail in (Cottineau et al., 2016).

One of the 5 work packages, the WP-EX, is in charge of organizing and carrying out a long term (2 year) road trial. The choice and instrumentation of the test site, the design of test plans and the common agreement submitted to the industrial partners were done by September 2015. The meaurements and data collection are carried out in partnership with the control officers, i.e. the motorway police, the DREAL/Services transport, the system suppliers and the motorway manager, SANEF, the concessionary motorway company.

This road trial aims at validating, with known test vehicles and vehicles picked from the traffic flow (and weighed in static), and in controlled and current traffic conditions, the metrological and functional ability of the proposed WIM systems to be used for direct enforcement. The two main steps are :

- to demonstrate the technical and metrological performances of the measuring instrument. The measures gathered and filtered by the WIM systems should meet the tolerances of the OIML class 5, which corresponds to the tolerances of the accuracy class A(5) of the COST323 European specifications of WIM (Jacob et al., 2002), but for 100% of the measurements instead of 90 to 95% for a non-legal application,
- to demonstrate the equipment functionality by constructing one or more prototypes of WIM system integrating all required functions for direct enforcement.

2. Tests site description

The trial site is located on the motorway A4 (Metz to Strasbourg), with 2x2 carriageways, near the toll gate of Saint-Avold (Figure 1). This motorway is equipped with a high speed WIM (HS-WIM) equipment for screening presumed overloaded vehicles upstream of a checking area fitted with a type approved static scale (Figure 2).

Figure 1 – Overview of the test site of St Avold (A4 motorway, SANEF)

Given the locations of the entries/exits of Boulay-Moselle and Saint-Avold, a test truck can achieve a rotation in 35 minutes, i.e. to make 8 runs on the WIM systems in one day.

Figure 2 – Saint-Avold toll gate (left), and check area with a static scale (right)

The motorway asphalt pavement was rebuilt in July 2014 and the site is in the class III (Acceptable) for WIM according to the COST323 Specifications. The section equipped with the WIM systems has a straight line of 130 m upstream and 190 m downstream. The longitudinal slope is less than 2% and the cross slope less than 2.5%. The pavement has a slight rutting, between 2 and 3 mm. The pavement deflection is in the range of 0.20 to 0.30 mm. The road evenness is vgood with APL ratings between 8 and 10 (IRI less than 2 m/km) over 1000 m. The average daily traffic (all vehicles) is 9632 in both directions, among them 2093 over 3.5 t, i.e. nearly 22%. The overload rate is 1.3%, including 0.24% with more than 10% overloading

3. Industrial partnership and systems installed

A call for participation have been launched to WIM manufacturers and vendors. They were invited to a laboratory test, an accelerated pavement testing facility test and on road trial. Companies marketing mature enough products and technologies to be assessed and improved if needed to meet the requirements of the direct enforcement were eligible as project partners. Sterela and Fareco (France), and Kapsch (Austria) joined the project in 2014. Sterela and Kapsch proposed piezo-quartz WIM sensors by Kistler (type G) and Fareco proposed piezo-ceramic sensors by Thermocoax. They all passed the laboratory and accelerated pavement testing facility tests in 2014-15, and installed their full WIM systems on the motorway test site in September 2015. Intercomp (USA) has expressed an interest, and passed successfully the laboratory test with a new sensor made of strain gauges. It is expected to install the Intercomp system on the motorway test site in June or July 2016.

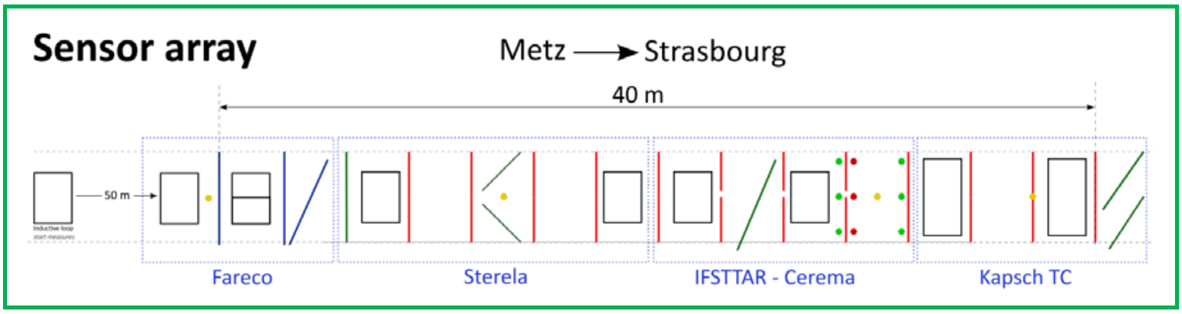


Figure 3 – WIM sensor layout in St Avold

In addition, IFSTTAR and Cerema installed a few more piezo-quartz sensors (type F) on the same site. The full set of sensors installed comprises (Figure 3):

- 14 weighing sensors, among them 12 piezo-quartz and 2 piezo-ceramics (Fareco),
- 10 inductive loops,
- 6 transverse location sensors (with an angle),
- 7 temperature sensors, 9 geophones and accelerometers at various depths (bullets on the Figure 5).

Each industrial partner provided the sensors, hardware, software and required knowledge to operate their systems, and installed them at on their own. Each company is responsible of the calibration and maintenance of its system all along the project duration, and shall comply with the rules of the motorway concessionary and the project leader. Each company provides to IFSTTAR and Cerema all gathered measurements (raw and elaborated) during all test periods and shall communicate all information useful for the implementation of its hardware and software. IFSTTAR and Cerema will keep confidential all information property of the partners and will not communicate to third party the raw data gathered by each system. Static weighing (reference) are provided to partners for all vehicles weighed by their system.

IFSTTAR and Cerema gives a feedback to each partner on their own system, above helping any improvement or adaptation to direct enforcement. The partners undertake to implement the changes and updates proposed by or jointly defined with IFSTTAR and Cerema provided that they are compatible with the system and the means available.

4. Presentation of the WIM systems

4.1 Sterela

Sterela installed a multiple sensor array to evaluate several configurations and to find the best one according to the accuracy/cost ratio. The system is composed of 2 electromagnetic loops, 8 piezo-quartz sensors forming 4 weighing lines, 2 piezo-polymer sensors in V-shape to determine the lateral location of the wheels, and a camera for reading license plates. The system provides in real time the weights measured by 2 piezo-quartz sensors. The output signals of all sensors are recorded and post-processed using a multiple sensor algorithm.

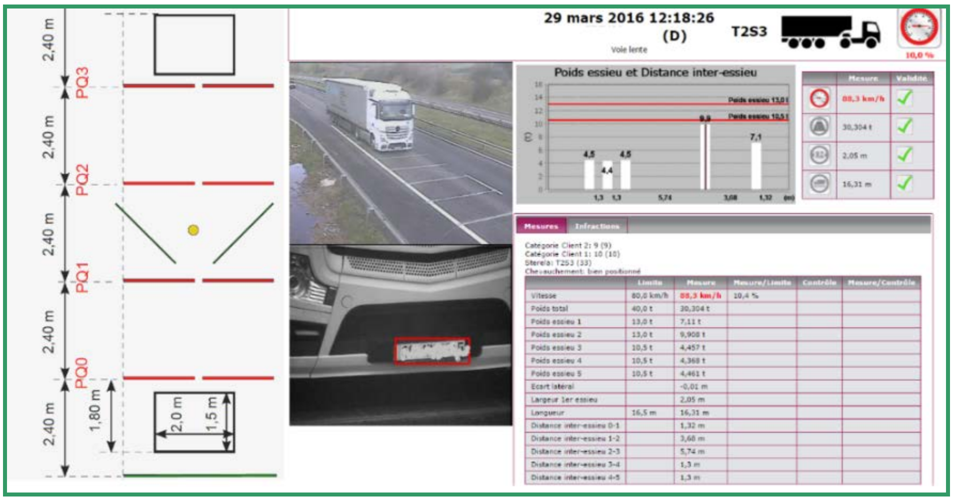


Figure 4 – Sterela WIM system: screen display

4.2 Fareco

The Fareco WIM system comprises (Figure 5):

- 2 piezo-ceramic weighing sensors (vitro ceramic Vibracoax®), piezo 1 and 2,
- 1 piezo-ceramic with an angle for lateral positioning of vehicle wheels, piezo 3,
- 4 inductive loops (numbered 1 to 4),
- a temperature sensor in the pavement,
- a SCC400 road side unit.

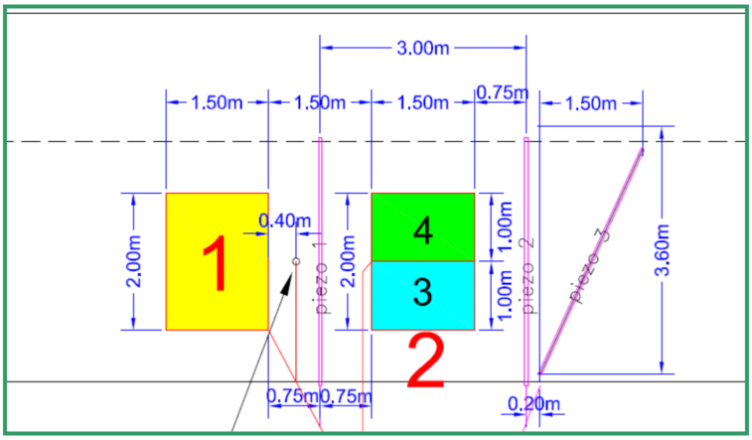


Figure 5 – Fareco WIM system

The features of each type of sensor and of the SCC-400 built-in algorithms are:

- to compensate the influence of the transverse location of the wheels because of some inhomogeneities along the WIM sensor its length,
- to calibrate individually each weighing sensor,
- averaging the weights mesured on each sensor to reduce the influence of the vertical accelerations,
- to adjust the weight of twin wheels, as they may induce specific electrical response of hte sensors,
- to compensate the effects of vehicle velocity and pavement temperature.

4.3 Kapsch

The HS-WIM system installed includes (Figure 6):

- 3 full lines of piezo-quarz weighing sensors (type G by Kistler),
- 2 piezo-polymer sensors with an angle for lateral positioning of vehicle wheels,
- 2 inductive loops,
- a camera reading the licence plates,
- a GPS antenna and a WIM controller.

Most of these components are mandatory but some are optional or could be added to provide additional data and functionalities. The WIM controller is fed with signals from the on road components to elaborate vehicle parameters, e.g. date and time of detection, lane, driving direction, head, gap, length, speed, number of axles, class, distance between axles, wheel weights, axle weights and gross weight of each vehicle. But it can also collect GPS signals (time), and pavement temperature.

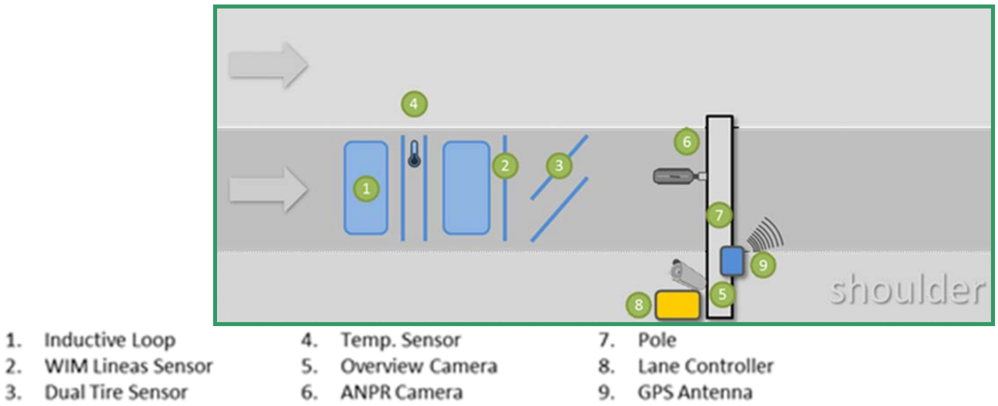


Figure 6 – Kapsch WIM system

The Kapsch WIM system also has a validity check feature. Invalid measurement due to driving behaviour or defects on vehicle runs are marked according to specified criteria, to be defined. This will help the system to comply with the direct enforcement requirements by putting flags on the measurement found within the tolerances, as far as the sorting and filtering algorithms will be developed.

5. Experimentation outlines

5.1 Main organization

The test data will be used to validate sorting and filtering criteria and algorithms, allowing HS-WIM systems to provide a subpopulation of vehicles weighed within the 5% tolerance required for direct enforcement. More than 15 days of measures are scheduled in 2015-2016 on the test site, with rented test lorries and trucks of the traffic flow stopped and weighed in static in the check area. Cerema organizes and manages these tets and collect measurements from all systems. The trucks of the traffic flow to be weighed in static are stopped by the police and then weighed on a static scale by the weighing officers of the regional DOT (Lorraine). The IFSTTAR and Cerema provide test trucks for system calibration, and assessment in repeatability conditions. The data are processed by Cerema and IFSTTAR.

5.2 Tests plan

The test plan and accuracy assessment procedure are based on the COST323 Specifications and on the OIML R134 International recommendation on WIM (OIML 2006). Measurements are carried out in repeatability and limited reproducibility condition with rented test vehicles of different silhouettes and loads, and in full reproducibility conditions with vehicles from the traffic flow (50 to 80 are catched per day). The raw signals of all sensors are gathered and stored for further in-depth analysis and comparison with those gathered on the accelerated pavement facility of IFSTTAR. In addition to the weights, other parameters are measured such as the lateral location of the trucks, the pavement strains, vibrations, and temperature, licence plate numbers, etc.

The three first days of measurements in September and October 2015 were devoted to calibrate and tune the systems. Up to seven test trucks (2- and 3-axle rigid and 5-axle articulated) were leased and made 8 runs each. Test trucks should be equipped with air suspensions for driving axles and groups of axles. Table 1 shows the test plans implemented as follows:

- speeds: 90 and 70 km/h,
- lateral locatons in the lane: centred and ±50 cm off-centred,
- load: half and full load.

Table 1 – Test plan for the 3 calibration days

Campaign duration	R-Conditions	Test vehicles	Speed		Lateral position			Load and passes				
			Sm	0,8 x Sm	Well-centred	50cm gap left	50cm gap right	Empty	Median load	Full load	Traffic trucks	Passes number
Calibration (1) 1 day	(R3)	2 x T2S3	5	3	8	-	-	-	-	8	-	16
		1 x T2S3	5	3	8	-	-	-	8	-	-	8
		1 x C3	5	3	8	-	-	-	-	8	-	8
		1 x C3	5	3	8	-	-	-	8	-	-	8
		1 x C2	5	3	8	-	-	-	-	8	-	8
		1 x C2	5	3	8	-	-	-	8	-	-	8
			35	21	56	-	-	-	24	32	**15**	**56**
Calibration (2) 1 day	(R3)	1 x T2S3	5	3	4	2	2	-	-	8	-	8
		1 x C3	5	3	4	2	2	-	-	8	-	8
		1 x C2	5	3	4	2	2	-	-	8	-	8
			15	9	12	6	6	-	-	24	**69**	**24**
Calibration (3) 1 day	(R3)	1 x T2S3	5	3	4	2	2	-	-	8	-	8
		1 x C3	5	3	4	2	2	-	-	8	-	8
		1 x C2	5	3	4	2	2	-	-	8	-	8
			15	9	12	6	6	-	-	24	**81**	**24**
											165	**104**

Legend: C2/C3 = 2-/3-axle rigid truck, T2S2/T2S3 = 4-/5-axle articulated truck (2-axle tractor and semi-trailer with tadem or tridem axles).

5.3 Data processing chain

Figure 7 gives the steps of data analysis and processing. A single data model was designed to cope with heterogeneous data from the three industrial partners. The data integration uses a software in the PostgreSQL database for each partner. A website was developed to store the data and to give access to local or remote users. Report templates are produced to get all industrial partners measures in an unique format, that can be exported to pdf or Mircrosoft Excel.

Figure 7 – Data processing chain

6. First results

6.1 Accuracy and performance assessment

Two assessments are or will be carried out on the data collected:

- assessment of the accuracy according to the COST323 Specifications (statistical approach),
- assessment for the direct enforcement (to be carried out).

The second assessment will only involve system equipped with correction and filtering algorithms and criteria, able to split the measured vehicles into 2 sub-populations:
(1) overloaded vehicles weighed within the direct enforcement tolerances (OIML class 5),
(2) other vechiles.

The results presented in section 6.2 relate to the first assessment according to the COST323.

A first set of filtering criteria was defined as:

- lateral offset in the lane; < ± 0.30 m,
- speed in the range: 80 - 100 km/h,
- gross weight = sum of axles weights ± 50 kg.

6.2 Sterela

Two sets of measures have been produced by Sterela depending on the sensor configurations:

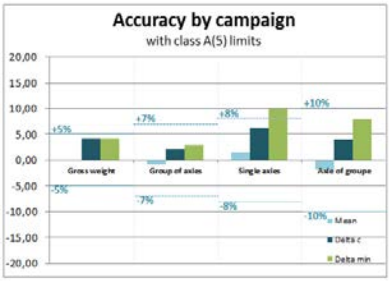
- two half-sensors data processed on time by the WIM system (noted Sterela 1),
- four lines of two half-sensors data processed by a computer model in deferred time (noted Sterela 2).

Figure 8 shows that for the three days of calibration, the COST323 accuracy classes B+(7) to B(10) were obtained for the test trucks and the trucks from te traffic flow. On two days out of three, the GVW accuracy was in class A(5).

15/10/2015 Sterela (1) — Known trucks

Conditions	Test plan	Env[t]
	R3	I

SYSTEM Entity	Number	Identified (%)	Mean (%)	Std deviat (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	δ_c (%)	π (%)	π (%)	Accepted class
gross weight	94	100,0	-0,01	1,94	94,9	A(5)	5	4,2	4,2	94,9	98,0	B+(7)
group of axles	66	100,0	-0,84	1,16	94,4	A(5)	7,1	3,0	2,1	94,4	100,0	
single axle	160	100,0	1,56	4,32	95,4	B+(7)	11	9,9	6,3	95,4	97,3	
axle of group	170	100,0	-1,83	3,25	95,5	A(5)	10	7,9	4,0	95,5	99,0	



09/11/2015 Sterela (2) — Trafic trucks

Conditions	Test plan	Env[t]
	R4	I

SYSTEM Entity	Number	Identified (%)	Mean (%)	Std deviat (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	δ_c (%)	π (%)	π (%)	Accepted class
gross weight	45	100,0	0,63	1,44	93,6	A(5)	5	3,4	3,4	93,6	99,5	A(5)
group of axles	45	100,0	-0,31	1,76	93,6	A(5)	7,1	3,9	2,7	93,6	99,9	
single axle	96	100,0	1,45	3,21	94,9	A(5)	8	7,6	4,7	94,9	96,2	
axle of group	130	100,0	-0,29	2,82	95,2	A(5)	10	6,2	3,1	95,2	99,9	

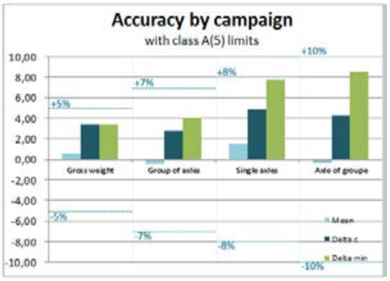


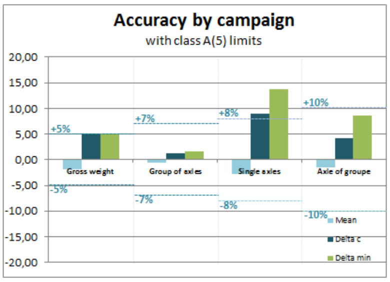
Figure 8 –Accuracy of Sterela system (COST323)

6.3 Fareco

The measures have been produced by a Fareco WIM system using two lines of ceramic sensors. Figure 9 shows that over the three days of calibration, the COST323 accuracy class B(10) was obtained for all trucks. On two days out of three, the GVW accuracy was in class B+(7).

09/11/2015 Fareco	Known trucks		
Conditions	Test plan		Env[t]
	R3		I

SYSTEM	Number	Identified	Mean	Std deviat	π_o	Class	δ	δ_{min}	δ_c	π	π	Accepted
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)	(%)	(%)	class
gross weight	36	100,0	-1,41	2,43	93,1	B+(7)	7	6,0	6,0	93,1	96,9	B(10)
group of axles	21	100,0	-0,14	1,10	91,1	A(5)	7,1	2,5	1,7	91,1	100,0	
single axle	66	100,0	-2,08	4,76	94,4	B(10)	15	11,2	7,2	94,4	99,1	
axle of group	57	100,0	-0,14	4,32	94,1	A(5)	10	9,5	4,7	94,1	95,5	



09/11/2015 Fareco	Trafic trucks		
Conditions	Test plan		Env[t]
	R4		I

SYSTEM	Number	Identified	Mean	Std deviat	π_o	Class	δ	δ_{min}	δ_c	π	π	Accepted
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)	(%)	(%)	class
gross weight	66	100,0	-0,05	3,15	94,4	B+(7)	7	6,9	6,9	94,4	94,8	B(10)
group of axles	42	100,0	0,20	1,13	93,5	A(5)	7,1	2,5	1,8	93,5	100,0	
single axle	114	100,0	-0,86	5,41	95,1	B(10)	15	11,9	7,7	95,1	98,8	
axle of group	108	100,0	0,63	4,28	95,0	A(5)	10	9,4	4,7	95,0	96,4	

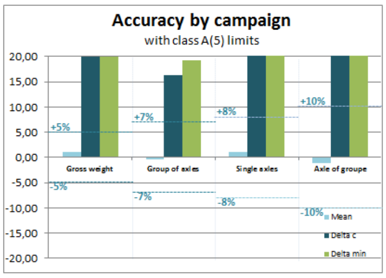


Figure 9 – Accuracy of Fareco system (COST323)

6.4 Kapsch

The system's motherboard belonged to a faulty series, which lead to a hard disk failure that was not detectable by monitoring and which unfortunately led to losing the data collected during the calibration phase. Both components have then been replaced and the system is up and running and thus will be able to give results when the campains resume.

6.5 Summarized results

The results of the calibration phase in real conditions are promising and accurate: the COST323 class A(5) has been reached on several days for the gross weight by one system, and the class B+(7) by the other one (Table 2). They reveal a proper installation and functionning of the systems. However, Tables 3 indicates that for none of the days 100% of the measurements fall within the tolerances of direct enforcement.

Table 2 – Global COST323 GVW results

Gross weights - COST323 Class			
	Sterela (1)	Sterela (2)	Fareco
15-10-2015 – Know trucks	A(5)	ND	ND
26-10-2015 – Know trucks	A(5)	ND	ND
09-11-2015 – Know trucks	A(5)	ND	B+(7)
15-10-2015 – Traffic trucks	A(5)	ND	ND
26-10-2015 – Traffic trucks	A(5)	A(5)	ND
09-11-2015 – Traffic trucks	A(5)	A(5)	B+(7)

Table 3 – Relative errors split

Relative errors repartition	Gross weight				Single axles			
	0%-5%	0%-10%	0%-15%	0%-20%	0%-5%	0%-10%	0%-15%	0%-20%
Sterela (1)								
+ Know trucks 15/10/2015	100%	100%	100%	100%	73%	98%	100%	100%
+ Know trucks 26/10/2015	100%	100%	100%	100%	73%	95%	100%	100%
+ Traffic trucks 26/10/2015	100%	100%	100%	100%	80%	98%	98%	100%
+ Traffic trucks 09/11/2015	97%	100%	100%	100%	85%	96%	100%	100%
Sterela (2)								
+ Traffic trucks 09/11/2015	98%	100%	100%	100%	86%	100%	100%	100%
Fareco								
+ Know trucks 09/11/2015	97%	100%	100%	100%	71%	96%	97%	100%

7. Summary and conclusions

Road test is a key and mandatory step to assess and validate WIM systems proposed for direct enforcement. Promizing results were gathered during the calibration phase with two systems using two types of piezo WIM sensors. One system encountered an electronic failure, which is now fixed. However the measurements did not fully met the requirements of direct enforcement, which prove that more advanced filtering algorithms are needed.

The on site measurements are continuing since April 2016 and will be complemented by in-depth analysis of the vehicle dynamics, of the influence of the road characteristics and driving conditions. Correction and filtering criteria and algorithms will be developed and checked within the trial.

8. Acknowledgements

Authors express their thanks to the DGITM (General Directorate for Infrastructure, Transports and Sea) of the French Ministry of Environnement, Energy and Sea, for supporting this project, to the DREAL, to the motorway concessionary company SANEF and to the industrial partners Sterela, Fareco and Kapsch.

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EVALUATION OF A HIGH SPEED WEIGHING STATION ON A BRAZILIAN HIGHWAY




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LabTrans	STERELA	EGIS	STERELA
Brazil	France	Brazil	France

Abstract

STERELA, EGIS Brazil and LABTRANS entered in an agreement in 2014 to run a long term high speed weigh in motion experiment in Araranguá, in the state of Santa Catarina, South of Brazil. In order to perform this experiment, an adapted pavement and a LSWIM system were provided by LABTRANS and a WIM system and infrastructure work by STERELA and EGIS. The objective was to prove that a system could adapt to the Brazilian context with a specific sensor grid (road, weather, classification), achieve a high accuracy with consistency, test the efficiency of a “validation criteria” that can allow to look towards automatic direct enforcement. Findings show that a highly efficient classification is possible (error less than 0.5%), that class B+(7) is a reasonable objective in terms of precision. Results are also fairly encouraging because they show that the validation criterias are effective in limiting the maximum error on the measures produced (107% without validation criteria, 18% with).

Keywords: Weigh-in-motion, WIM, validation criteria, pre-selection, direct enforcement, legal metrology, INMETRO, COST 323

Résumé

STERELA, EGIS Brésil et le LABTRANS ont signé un contrat de coopération en 2014 dans le but d’organiser un projet pilote de pesée à haute vitesse sur le long terme à Araranguá, Sud du Brésil. Dans le but de mener à bien ce projet, une chaussée adaptée ainsi qu’une balance de pesée basse vitesse ont été fournis par le LABTRANS ; l’infrastructure et le système WIM ont quant à eux été fournis par EGIS Brésil et STERELA. L’objectif était de prouver que le système WIM puisse s’adapter au contexte Brésilien avec une grille de capteurs spécifique (chaussée, climat, classification), réussir à obtenir une haute précision avec consistance dans le temps, tester l’efficience de la fonction « critère de validation » qui pourrait permettre de mettre en place un Contrôle Sanction Automatique. Les résultats montrent une haute précision possible au niveau de la classification (erreur inférieure à 0,5%), que la classe B+(7) est un objectif raisonnable en termes de précision. Ce sont des résultats encourageants quant au critère de validation puisqu’ils montrent que ce dernier est efficace en limitant l’erreur maximale sur les mesures produites (107% sans le critère de validation, 18% avec)

Mots-clés Pesage en marche, WIM, critère de validation, présélection, verbalisation automatique, métrologie légale, INMETRO, COST323

1 Introduction

In November 2014, EGIS Brasil and Sterela installed a GLOBAL-WIM weigh-in-motion system in the city of Araranguá in the state of Santa Catarina. This station is operated in Brazil by LabTrans (Transportation and Logistics Laboratory) from the Federal University of Santa Catarina (UFSC) and received a French grant in the framework of a FASEP project (funds for studies and assistance in the private sector).

The primary objective of this project is to demonstrate the ability of the GLOBAL-WIM station to preselect overloaded vehicles, taking into account the specific environmental and traffic conditions in Brazil. It will become a demonstrator of the capabilities of a free-flow control station as described in the call for tender issued by the Brazilian National Department for Transport Infrastructures (DNIT) for the new concept of weigh enforcement in Brazil entitled as Integrated Automated Fiscalization Station (PIAF).

The second objective is to carry out a feasibility study on the automatic weight enforcement in Brazil. This will naturally include an assessment of weigh-in-motion performance, as well as a study of Brazilian legislation on the subject. The next stage will be to verify the ability of the GLOBAL-WIM system to recognize the differential criteria by which the system identifies the category of vehicle and therefore its corresponding legal weight limit.

2 Installation

The first WIM station in Brazil was put together from a worldwide research and installed in the late 70's, until today no new major development was made concerning the way it operates. Since the beginning all heavy vehicles should enter the station premises and slow down to 60 km/h to pass through a pre-selection scale. If the vehicle is supposedly overloaded it is directed to the slow speed scale otherwise diverted back to the highway. One of the PIAF concepts is to preselect offenders on the highway, hence the study in the advances of technology using the WIM system. This new technology mainly benefits truckers that are within the legal weight limits, as they don´t have to slow down and enter the station, also it minimizes the possibility of truck lines waiting to be weighed at the station.

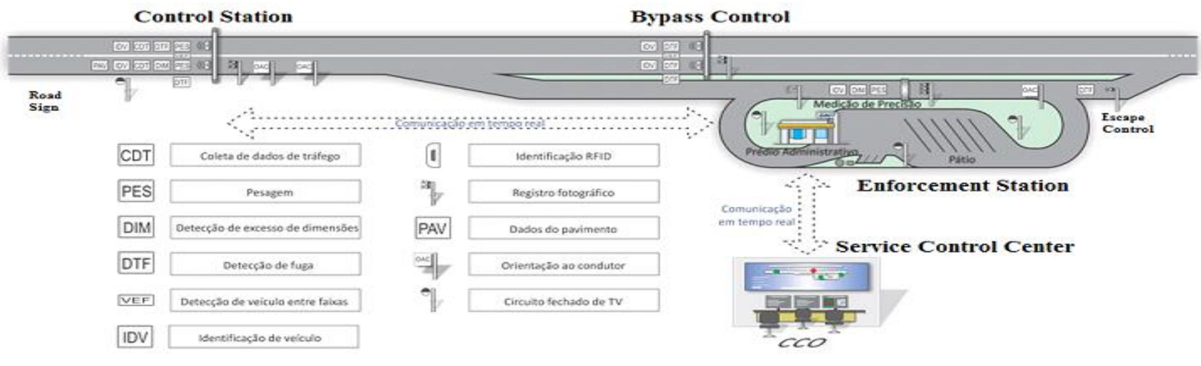

Figure 1 – PIAF synoptic

2.1 Road structure

The pavement structure was specified to meet the eligibility criteria of a Class 1 site ("excellent") according to the COST323 pre-standard (Jacob, O'Brien, Jehaes, 2002). It was completely rebuilt over a length of 200 m. The pavement structure is a flexible type and it consists of 6 layers. The top layer does not contribute to the pavement structurally but it assures safety and comfort as well as good resistance to wear and tear. The second is made with asphalt mixture of elevated module. The next two layers are made with the same composition which is asphalt treated base, they are divided in two parts as they are compacted in both layers. The fifth segment is constructed with crushed rock and the foundation utilizing sand treated with lime. The road rebuild was accompanied by LabTrans engineers to assure the quality of all steps of the pavement materials and construction.

Table 1 - Road structure

Pavement Layer	Thickness	Acronym	Asphalt Cement / Lime	Granular Material
Surface Course	6 cm	BBM	5.0% CAP 30/45	Crushed Rock ¾: 25%
Asphalt Dense Mix	12 cm	EME 1	5.5% CAP 30/45	Gravel: 25%
Granular Base + Asphalt Cement	12 cm	GB 3	4.2% CAP 30/45	Rock Dust: 45%
Granular Base + Asphalt Cement	12 cm	GB 3	4.2% CAP 30/45	Filer: 0.05%
Crushed Rock Sub-base	30 cm	Sub-base		Crushed Rock 0/31.5
Subgrade Stabilized with Lime	Last meter	AR 2	5.0% hydrated lime	Sand

Figure 2 – Road during and after rebuilding

2.2 WIM Sensors layout

The GLOBAL-WIM station in Araranguá interfaces with a grid of weighing sensors installed in the slow lane. A system that automatically reads the license plate number and takes a ¾ profile photo of the vehicle has also been installed.

The weighing grid consists of:

- Two magnetic loops (blue squares)
- Two rows of piezo-quartz sensors (red lines)
- Two piezo-polymer sensors in a V-shape (black lines)
- One temperature sensor (green circle)

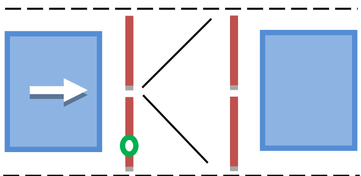

Figure 3 : Sensors layout

The weigh sensors are capable of detecting information about the vehicle's total weight and weight per axle, the lateral position of the vehicle in its traffic lane and the category of the vehicle, taking into account the type of axle (single or twin wheels). A template for installation was used to guarantee the geometric characteristics (alignment and parallelism) of the sensors on the weighing grid.

Figure 4 – Final installation

3 Performance analysis

3.1 Low speed scale

The reference weights were provided by a low-speed (2 to 6km/h) axle-weighing scale located a few kilometers downstream of the site and tested according to the specifications of the Brazilian National Institute of Metrology, Quality and Technology (INMETRO, 2013). This scale is operated by LabTrans.

The scale is calibrated once a year (the first time on 16 January 2015). At that time, the scale returned performance on total weight measurement equivalent to accuracy class 2 according to OIML R 134 (±1% error on initial verification and ±2% error for in-service)

The INMETRO criteria are as follows:

- Mean GVW value must fall within ± 0,5% of reference value
- Mean GVW value ± 2 standard deviations must fall within ± 3% of reference value
- Mean axle/group of axles value ± 2 standard deviations must fall within ± 3% of mean value.

3.2 Identification of vehicles

Correlation between the WIM system and the low speed scale is done by license plate and limited by a window of ±10 minutes for each event as well as equal number of axles filter.

3.3 Brazilian legislation and classification

DNIT has organized a manual (DNIT, 2012) containing all the configurations of commercial vehicles, which contains over 150 types of trucks and buses. The specifications consists the total length, inter-axles spacing and axle tire configuration. The first two are obtained by the magnetic loops and piezo-quartz, and the tire configuration using the piezo-polymer sensors in a V-shape format.

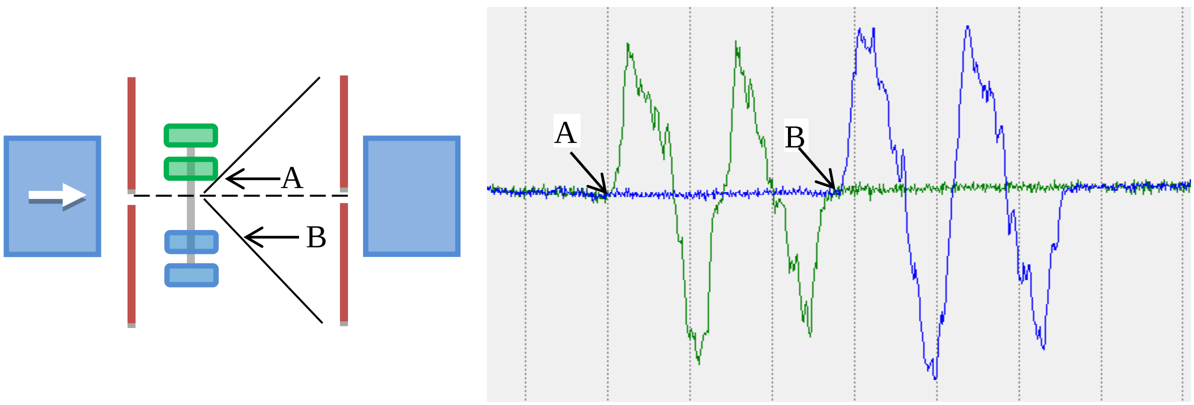

Figure 5 – Double tires passing by sensor and sensor signal

According to the Brazilian legislation, weight limit depends if axles are equipped with double wheels or not. The system already produces the information of double or single wheel but it has not been applied to the classification algorithm. As a consequence, the system will not yet be able to distinguish for example the 3C, 3CD or 3DC class and will group those trucks in the same class and with the higher weigh limit for these classes. However, this new feature will be implemented in the system in the next few months.

It has been estimate the accuracy of the classification by comparing, for each truck, the class provided by the low-speed scale and the class provided by the GLOBAL-WIM station:

- If classes are the same, the class is considered to be exact,
- If classes are different, the class is manually verified by the picture of the truck.

Table 2 - Classification accuracy (estimation)

Vehicles number (2015/03/19 to 2015/10/23)	14421
Classification errors	55
	0.44%

3.4 Breakdown of vehicles weighed at low speed scale

The categories of vehicles weighed at the low speed scale can be distributed as follows: it can be seen that the four overriding categories are respectively 3S3, 3C, 2S3 and 3I3, which between them account for 68% of the vehicles weighed.

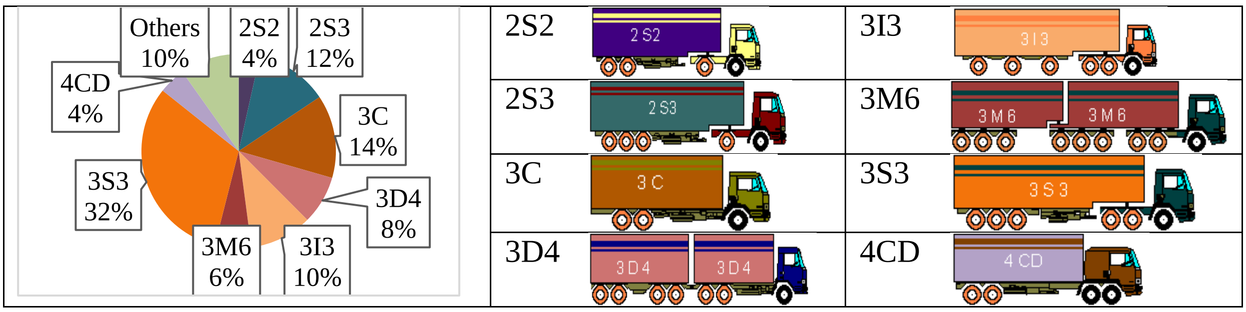

Figure 6 –Breakdown of vehicles weighed at low speed by category

Total weight of vehicles weighed at the low speed scale can be broken down as follows:

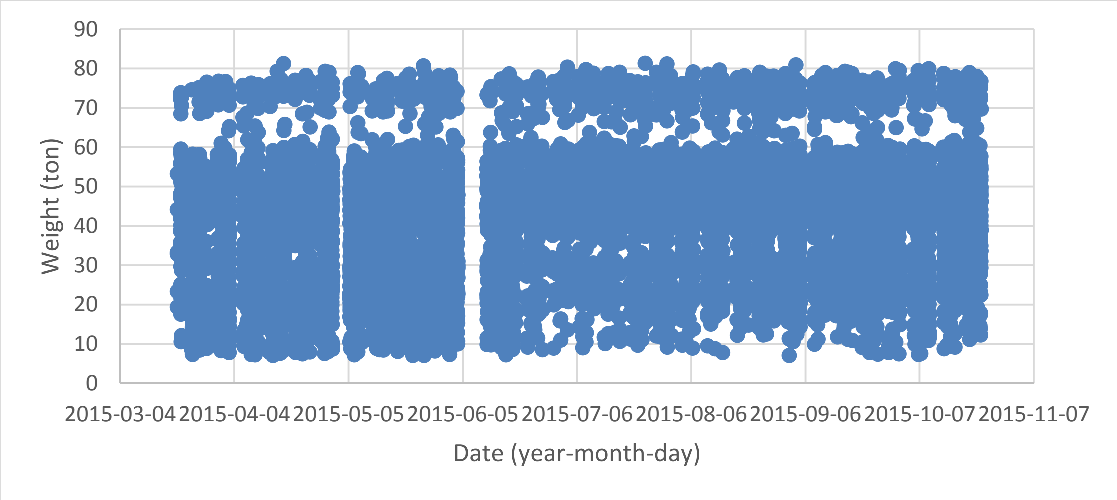

Figure 7 – Breakdown of vehicles weighed at low speed by GVW

It can be noticed that the number of vehicles weighed at low speed with a total weight of less than 20t decrease from June onwards. In fact, with the updates done in the control software, the Weigh Station operators were able to manually pinpoint vehicles which were more likely overweight and pull them over to the low-speed scale. Reasons for that include:

- Local traffic authorities instructed to avoid bothering empty or partially-loaded vehicles on the highway.
- Since the system is being evaluated mainly for enforcement related purposes, this paper focuses on the performance assessment on fully-loaded vehicles.

3.5 Results

The data presented in this section concerns only the **gross vehicle weight,** because at this stage of the study the data concerning weight per axle and data by group of axles is not yet available.

3.5.1 Breakdown of vehicles

The vehicles have been divided into two cases:

- All vehicles (except vehicles straddling two traffic lanes)
- Only vehicles validated by the weigh-in-motion system

Each time the vehicle passes through the station, the weighing system checks the integrity of the measurements provided by the sensors. If an inconsistency is detected, the system may invalidate certain measurements as:

- If measurement cannot be performed, the system invalidates the vehicle without providing any measurements.
- If the measurement can be calculated, the system provides it for information but indicates to the user that this measurement is not guaranteed to be accurate.

The criteria for the validity of weight measurements are, among others, the difference between measurements at the entry weighing line and the exit weighing line. If the difference is greater than 10%, the weight measurement is invalidated. This criterion invalidates a high number of vehicles at the Ararangua site because the bump located upstream of the site causes

vehicles to sway considerably, leading to a significant variation in measurements of weight per axle recorded by each of the weighing lines.
The following number of vehicles was taken into account each month:

Table 3 - Breakdown of vehicles by cases

2015	Vehicles	All vehicles[1]	Validated
March	Number	451	43
April	Number	1660	161
May	Number	1977	372
June	Number	1490	258
July	Number	2133	293
August	Number	2186	316
September	Number	2464	390
October	Number	2060	326
Total	Number	14421	2159
	Percentage of inspected vehicles	99%	15%

3.5.2 Mean error

The mean error calculated by month is as follows:

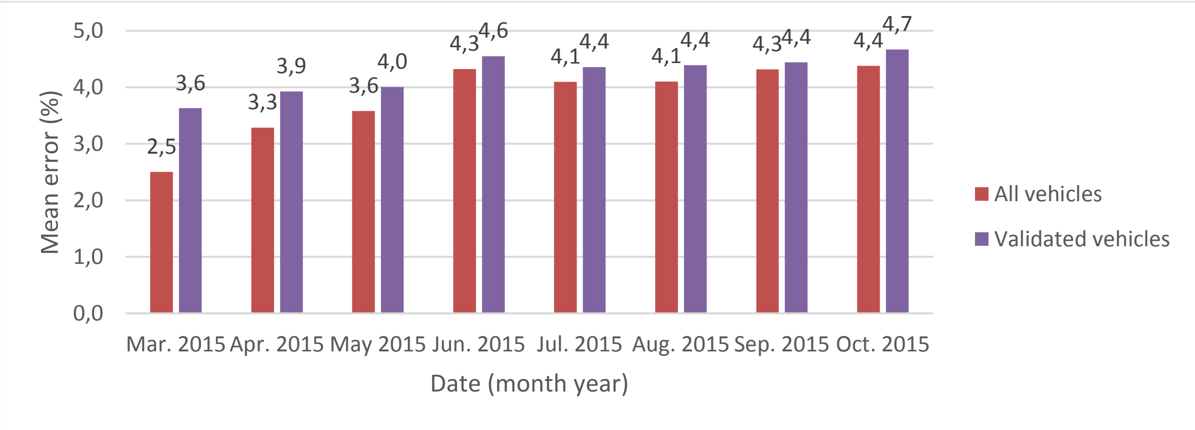

Figure 8 – Changes in mean error for all vehicles

It can be seen that the mean error is high, whereas the purpose of the initial calibration of the system is to reduce the mean error close to 0. This can be explained by the fact that the station were unable to calibrate with the low-speed scale data (not yet in operation when the WIM system was installed), which reduces the system's final accuracy class.

[1] Except vehicles straddling lanes

3.5.3 COST323 accuracy class

The COST323 accuracy class was calculated during the trial period:

Table 4 - COST323 accuracy class

2015	Vehicles	All vehicles	Validated
March	Number	451	43
	Confidence level	94%	97%
	Class	B+(7)	B(10)
April	Number	1660	161
	Confidence level	98%	98%
	Class	B(10)	B(10)
May	Number	1977	372
	Confidence level	99%	99%
	Class	B(10)	B(10)
June	Number	1490	258
	Confidence level	99%	98%
	Class	B(10)	B(10)
July	Number	2133	293
	Confidence level	99%	98%
	Class	B(10)	B(10)
August	Number	2186	316
	Confidence level	99%	98%
	Class	B(10)	B(10)
September	Number	2464	390
	Confidence level	94%	99%
	Class	B(10)	B(10)
October	Number	2060	326
	Confidence level	99%	98%
	Class	B(10)	B(10)
Over the period	Number	14421	2159
	Percentage of inspected vehicles	99%	15%
	Mean error (%)	3.99%	4.34%
	Standard deviation (%)	2.82%	2.55%
	Reproducibility	R2 (II)	R2 (II)
	Confidence level	98%	99%
	Class	B(10)	B(10)

3.5.4 Standard deviation

The standard deviation calculated by month is as follows:

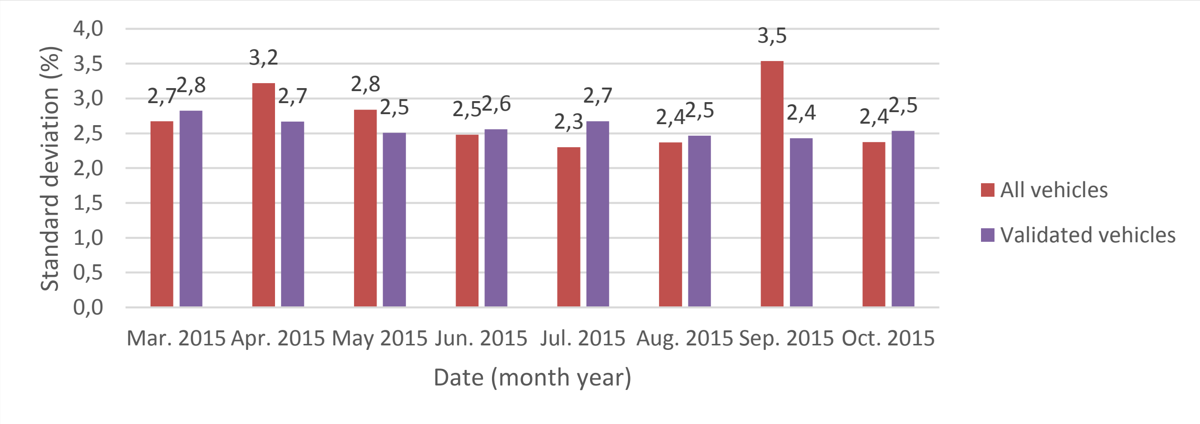

Figure 9 – Changes in standard deviation for all vehicles

It can be seen that the standard deviation for validated vehicles is relatively stable for the entire period, at around 2.5%.

3.5.5 Inspection with automatic penalties

The main challenge is to make the WIM stations compliant with the requirements of legal metrology, which requires 100% of the measurements to be accurate within the maximum permissible margin of error. To accomplish this, WIM stations must be able to automatically detect and eliminate from their measurements all values considered uncertain from validation criteria based on the analysis of the dynamic behavior of vehicles.

The table below presents the results obtained taking into account all vehicles and validated vehicles:

Table 5 - Calculation of maximum error measurement

Evaluation according to Automatic Overload Penalty system	All vehicles	Validated
Number of vehicles	14,421	2,159
Maximum permissible margin of error	10%	10%
Maximum error measured	107%	18%
Number of false positives	192	35

It can be seen that the number of false positives decreases considerably on the population of validated vehicles. The number of false positives is also consistent with the confidence level required for the COST323 accuracy class.

It should also be noted that the system's high mean error obviously has an influence on the maximum error measured. Instead of being centered on 0, the systematic bias (approximately 4%) has a tendency to increase the number of false positives with a measurement error greater than +10%.

This is shown on the graph below:

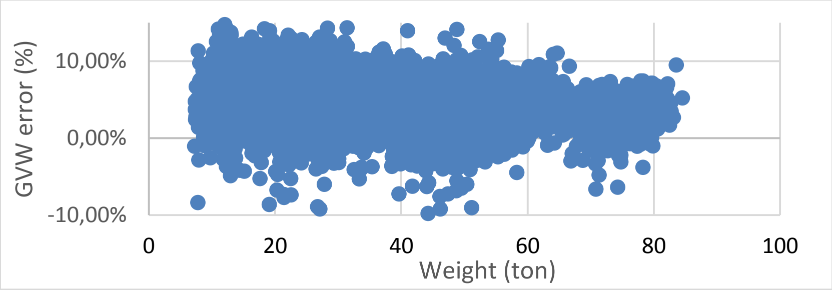

Figure 10 - Breakdown of measurement errors by vehicle weight

4 Conclusion

Vehicle classification performance was highly efficient (error less than 0.5%) even if the double wheel information must be taken into account to distinguish more classes.

COST323 accuracy class test extends over 8 months of collected data, with a large sample of vehicles taken from the traffic flow. The accuracy class B(10) in conditions II-R2 was achieved throughout the period. The system's final accuracy class should however be better (at least B+(7)) because it should be possible to considerably decrease the mean error by performing calibration based on the data from the low-speed scale used for these tests.

Inspection with automatic penalties results are fairly encouraging because they show that the validation criteria are effective in limiting the maximum error on the measures produced (107% without validation criteria, 18% with). However, we should still deal with two issues:

- Validation criteria exclude 85% of the vehicles: this is due to the significant swaying of vehicles related to the "bump" located upstream of the site. This issue will be fixed by grinding the “bump”. This should be done in 2016.
- False positives: validation criteria must still be improved to eliminate all false positives. This is the main challenge for this project in Brazil as well as the “CSA (Contrôle Sanction Automatisé) overload” project in France and the “direct enforcement” project in Belgium.

The Araranguá GLOBAL-WIM weighing station already demonstrates what a free-flow control station for the PIAF project could be. It demonstrates the capacity of the system to provide the expected results in terms of both weighing accuracy and vehicle recognition. It opens the way in Brazil for pre-selection weigh-in-motion stations to migrate towards the automatic issuing of fines.

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QUALITY CHECKS FOR WEIGH-IN-MOTION DATA IN EUROPE

Mr. van Loo has been involved in the field of Weigh-In-Motion technology and applications for more than 20 years. Since 2013 he has been working as an independent expert and consultant for both users and vendors of WIM systems.

Mr. Lees joined TDC Systems in 2010, prior to this he worked for 35 years with the UK Governments Department for Transport where he was Head of the automatic traffic and weigh in motion statistics branch. He has been involved in the field of Weigh-In-Motion for more than 20 years.

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Abstract

This paper describes the development of a simple management test to make a first assessment of the quality of the data measured by Weigh-in-Motion (WIM) systems as part of the European EcoVehicle project ∑!7219. First the background, reasons and requirements for such a test are explained. These are followed by an explanation of the starting points and the approach used in the development of the test and its criteria. The individual quality checks and criteria were evaluated using actual WIM data from sites in four different European countries. An overview is given of the current procedures for the management of the quality of data in different European countries. Finally, a summary is provided presenting the main conclusions and recommendations for the future application of these tests and their potential to serve as a basis for an international reference data quality assessment tool.

Keywords: WIM, Footprint, EcoVehicle, Data, Quality, Checks, Validation

Résumé

Cet article décrit le développement d'un test de gestion simple pour faire une première évaluation de la qualité des données mesurées par des systèmes de pesage en mouvement (WIM) dans le cadre de la EcoVehicle européenne projet ∑! 7219. Tout d'abord, le contexte, les motifs et les exigences pour un tel test sont expliqués. Elles sont suivies par une explication des points de départ et l'approche utilisée dans le développement du test et ses critères. Les contrôles de la qualité individuelle et les critères ont été évalués à l'aide de données réelles de WIM de sites dans quatre pays européens. Un aperçu est donné des procédures en vigueur pour la gestion de la qualité des données dans différents pays européens. Enfin, on trouvera un résumé présentant les principales conclusions et recommandations pour l'application future de ces tests et leur capacité à servir de base pour un outil d'évaluation de qualité des données standard international.

Mots-clés: WIM, Footprint, EcoVehicle, données, qualité, vérifications, validation

1. Background

One of the objectives of the Eureka Footprint project ∑!2486 (Mayer, 2009) was the development of a method to identify vehicles by means of their "Environmental Footprint". The damage caused by the dynamic loading of a heavy vehicle on the road – and rail – infrastructure is one of the aspects of a vehicle's environmental footprint. The quality (accuracy, reliability and stability) of the measurement data used in any study directly determines the quality of the results and conclusions of the study. The WIM data from different European countries used in the Footprint project (Poulikakos, 2009) have shown variability that could not be explained by mere differences in the national loading regulations alone. The differences in the data may have originated from variations in the local traffic flow, the environmental conditions or from differences in performance of the WIM systems, e.g. the type of WIM technology used or, possibly, structural measurement errors.

For a realistic comparison of the environmental impact of different vehicles – and in fact any other study on the impact of heavy truck traffic - the quality of the WIM data must be verified. This is especially important when comparing the effects in different European countries since the measurement data will come from different WIM systems based on different technologies, operating under different conditions and owned by different users. At present there is no uniform European standard procedure to make an assessment of the quality of WIM data from different systems. As a result, many studies may be based on WIM data with little - if any - idea of the quality of the data and as a consequence some conclusions may be based on erroneous data.

A full guarantee of the quality of WIM data can only be given after an extensive evaluation of the performance of the WIM system, the traffic and environmental conditions over a long period of time (e.g. 1 year). In most cases, such an extensive evaluation is too time consuming, too expensive to carry out and also too complicated since it requires an in depth knowledge of WIM systems and sensor behaviour. A limited and simplified evaluation could fill the gap between an extensive and expensive test and no test at all, allowing for a quick assessment of the quality of the WIM data.

2. The EcoVehicle ∑!7219 Project

The goal of this European cooperative project is defining road and rail vehicles with a low environmental footprint (Lees, 2014). The principal tasks include: analysing data from real time measurements, defining limit values for environmental friendly vehicles and defining a combined environmental index for vehicles. An important EU objective is to reduce the environmental impact of transport. Characterising the environmental impact of individual vehicles enables the polluter pays principle to be applied to land transport. One of the parts of the EcoVehicle project focussed on the dynamic loading of heavy vehicles and included:

a. the development of a limited and simplified evaluation for a quick assessment of the quality of the WIM data;
b. the first international benchmark on the data quality management, procedures and criteria used by different users of WIM systems in Europe.

It is hoped, this project could lead, in time, to the direction of a harmonised European criteria and procedures for Data Quality Management for WIM systems. This paper will describe the results from both parts.

3. Data Quality Assessment

3.1 Objective

No WIM system can produce perfect data, even with high quality equipment and ideal site conditions. Data files are more than likely going to contain some invalid data. Regardless of the minimum data quality requirements are, any WIM system should be monitored and maintained to produce the best possible data given the system's potential. The key is to keep bad data to a minimum and to quickly recognise, identify, isolate and correct the cause of erroneous data. (FHWA, 2009)

Therefore, the objective of this part of the project was to develop a basic set of tests and criteria that will allow the user to make a quick verification of the quality of the data from any WIM system in Europe. These tests could then be used to compare the relative quality of different WIM sites (the quality of the data from site A is better than that of site B) and, if possible, to give an indication of the absolute quality of the data of a particular site (the data from site C has a quality that is sufficient). It is important to realise that these quality tests will not be able to distinguish between variations in the measurements by the WIM system and variations in the truck traffic at a certain site. This means, that in case the test results would produce an "insufficient" verdict on the quality of data due to large variations in the WIM data, the reason for this could be explained by variations in the traffic flow and not because of the WIM system. In this case, the results of the tests should be interpreted as: "Do not use this data without additional checks on the quality of the data."

In general, the tests will look at the stability of certain elements or characteristics of the measured data. These tests will provide an idea of the relative quality of the WIM data however may still contain a stable – and possibly significant – measurement error. The selection of the characteristics was based on an evaluation of international literature on WIM data quality management and the practical experience from the authors:

- The United States, the Long-Term Pavement Performance (FHWA, LTPP) program initiated by the Transportation Research Board, the Federal Highway Administration and the American Association of State Highway and Transportation Officials (FHWA, 2010);
- The Netherlands, the WIM-NL network (currently consisting of 20 systems) developed by Rijkswaterstaat and used by the Transport Inspectorate for their weight enforcement program (Telman, 2013);
- South Africa, the South African National Roads Agency Ltd (SANRAL) has developed statistical methods for the calibration and quality assessment of the data from their network of about 50 WIM systems (De Wet, 2010).

3.2 Starting Points

In the development of the checks, the following starting points were used:

- the tests should give a first indication of the quality of the data measured by a certain WIM system;
- the tests should be easy to perform by anybody irrespective of whether they are specialists in Weigh-In-Motion or statistics or not;
- the calculations required for the tests should be available – or be easy to implement - in standard software like Excel, Access (or similar);
- it should be possible to do the tests on all measurement data from all different WIM systems currently operational in Europe;

- these tests should be carried out on a limited sample of the WIM data only, e.g. one week and should be representative of normal operational conditions.
- the test sample should be large enough to include possible variations over a few days and be small enough to be handled in Excel.

3.3 Quality Checks and Criteria

Determination of the tests and criteria to assess the quality of the data. In other words this means finding characteristics of certain types of vehicles that show a very small variation in daily practice and are commonly found throughout Europe. This can either be caused by international regulations for heavy goods vehicles (examples 1 and 2) or by standards in vehicle design (examples 3 and 4). The following examples of such characteristics were used in the quality checks:

1. The vehicle length of Truck+Trailer combinations and that of Tractor+Semi-trailer (articulated) combinations. For most EU member states the maximum allowable lengths for these combination are respectively 18.75m and 16.50m;
2. The Gross Vehicle Weight (GVW) of 3 axle Trucks and that of 5 axle Tractor + Semi-trailer (articulated) combinations. For most EU member states the maximum allowable GVW's for these combination are respectively 26ton and 40/44ton;
3. The axle load of the first (steering) axle of – fully loaded - 5 and 6 axle articulated vehicles. International experience has shown that the load on this axle lies normally in a narrow bandwidth between 6.5 and 7.0 tonnes;
4. The axle distance between the 2nd and 3rd (driven) axles of 6 axle Tractor + Semi-trailer combinations. International experience has shown that the distance between these axles is very stable at 1.30m as this allows the highest axle loads;

3.4 Sample Data

The objective was to collect a sample of WIM data (one week of data in case of a WIM-site with high traffic volumes) from different users, different countries and different technologies. The aim was to try to collect more data from different countries, if possible based on different technologies and if possible data from 'good' and 'bad' quality sites to be able to see if the criteria are able to detect the bad data.

For the project, measurement data from two sites in each of four different European countries have been collected and evaluated. We have also deliberately included a ninth site which we knew was not working correctly and therefore providing erroneous data. We have included this site to highlight the ability to identify faulty sites using these tests. This site will appear as Site 9 in the graphs and tables.

It should be stressed that in all cases, the exact location of the WIM sites, the type of equipment deployed and the manufacturers have been kept anonymous to ensure any unintentional bias cannot be applied to the results. It was also felt that anonymity of the equipment should be maintained to avoid any unnecessary comparisons between technologies and vendors since this is not the objective of this project.

4. Data Analysis

4.1 Gross Vehicle Weight

The first analysis was carried out on the type of articulated goods vehicle that is probably the most frequently encountered vehicle on European roads; the two axle tractor and three axle semi-trailer unit.

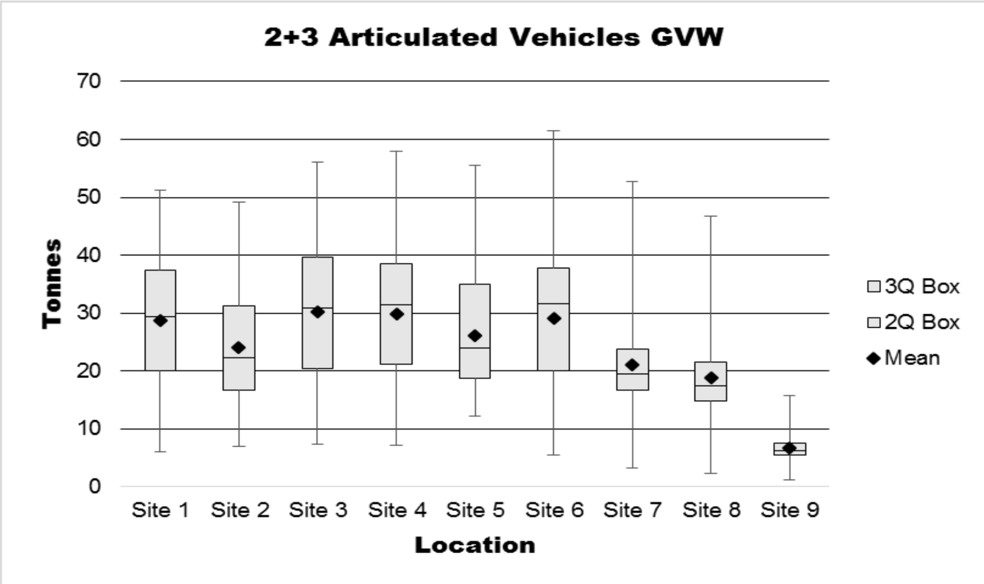

Figure 1 – Analysis of 5 axle articulated vehicles

Table 1 – Overview of 5 axle articulated vehicles

Site	1	2	3	4	5	6	7	8	9	Average
Mean	28.62	24.09	30.21	29.79	26.02	29.04	20.99	18.78	6.60	28.21
St. Dev	9.18	8.42	10.19	9.53	8.95	9.55	6.64	5.85	1.94	10.38

The average GVW for five axle articulated trucks is expected to be between the maximum permissible weight (40-44 tonnes) for international transports and the weight of empty trucks (around 20 tonnes). Hence an average value somewhere between 25 and 30 tonnes with a variation of ±10 tonnes could be expected. When looking at the chart in Figure 1 it is clear that there is a discrepancy using sites 7 and 8 in any further analysis as the average weights are significantly lower than those seen elsewhere. Whether this is down to a measurement error in the data or local traffic conditions, it is unsure without further inspection. For site 9 the average GVW is extremely low and it was known that the data was faulty.

4.2 Steering Axle Load

For the next test, the steering axle weight of two axle tractor + three axle trailer articulated combinations was examined. More specific the axle loads of the first steering axle of these vehicles when fully laden were examined, i.e. in excess of 30 tonnes gross vehicle weight (GVW). Obviously this was reliant on the “accuracy” of the test data to determine whether 30 tonnes GVW was met but this limit is actually not very strict and the results were rather consistent. For these next two tests it is clear from the previous results that Site 9 would not be able to be tested as none of the records for this vehicle class was measured in excess of 30 tonnes.

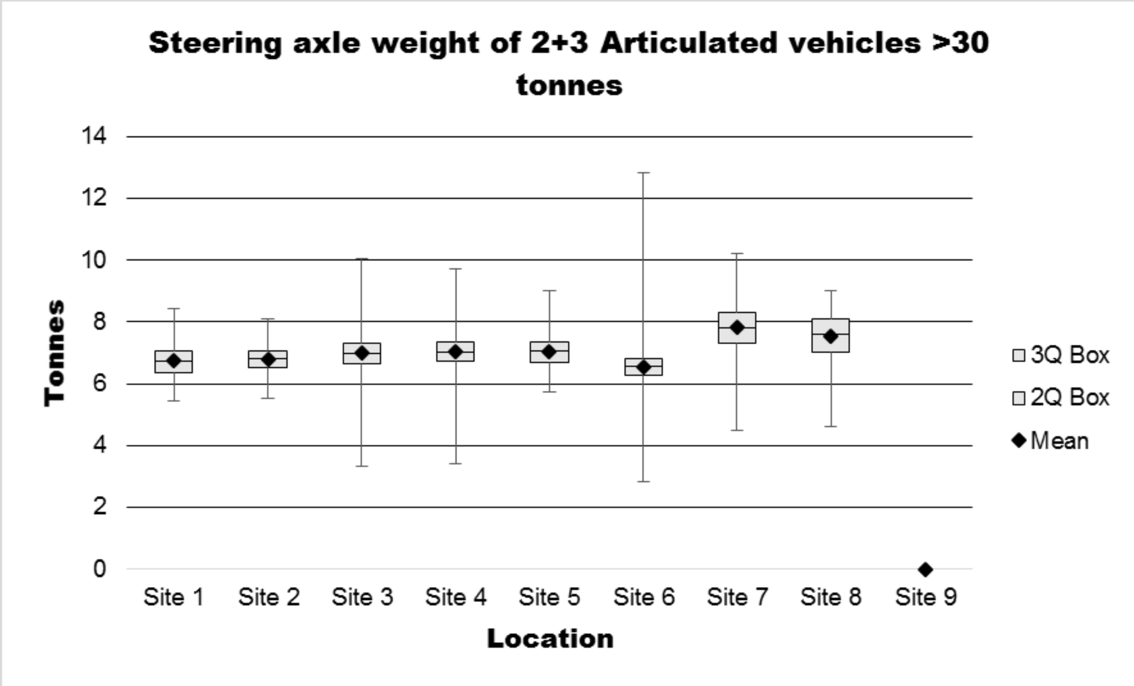

Figure 2 – Analysis of 1st axle load of five axle articulated vehicles

Table 2 – Overview of 1st axle load of 5 axle articulated vehicles

Site	1	2	3	4	5	6	7	8	9	Average
Mean	6.73	6.79	6.99	7.03	7.03	6.54	7.84	7.55	0	6.97
St. Dev	0.55	0.44	0.54	0.50	0.52	0.46	0.82	0.74	0	0.55

If site 6 is removed from the analysis, it has some extremes, the mean weight of the steering axle falls within 1 tonne of each other and there appears to be consistency in the 2nd and 3rd quartiles. Based on international experience the expected value for the first axle load is between 6.5 and 7.0 tonnes with a small variation. The first six sites follow these expectations, while sites 7 and 8 do appear slightly out of line with a higher average axle load and a larger variation. This should then alert the user to perhaps consider applicability of using the data from those sites in any analyses. Especially when this is combined with the lower average GVW for this vehicle class at these two sites.

Again the reason for these differences could also originate from the characteristics of the truck traffic at the site, e.g. a high percentage of light – partially loaded - vehicles that obviously have a lower GVW but tend to have a slightly higher axle load on the first axle because of a different distribution of the loads.

4.3 Vehicle Length

In addition to the two weighing related tests at 4.1 and 4.2, we checked vehicle length, a parameter that is not reliant on the WIM sensors but the inductive loops. This time, again using the same >30 tonne articulated two axle tractor/three axle trailer combination.

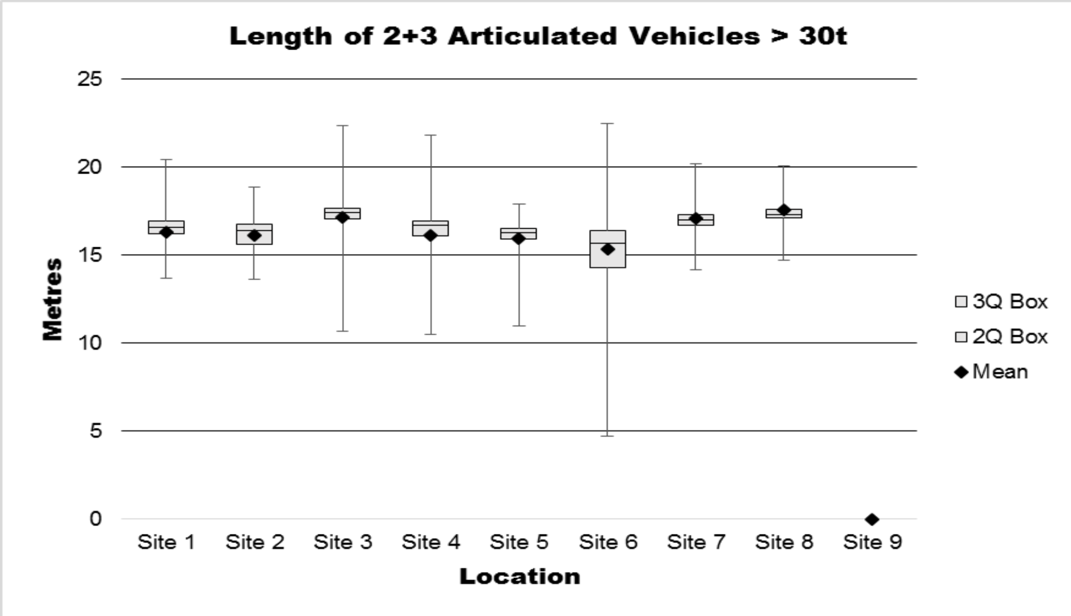

Figure 3 –Analysis of length of 5 axle articulated vehicles

Table 3 – Overview of length of 5 axle articulated vehicles

Site	1	2	3	4	5	6	7	8	9	Average
Mean	16.29	16.13	17.15	16.14	15.95	15.33	17.09	17.56	0	16.39
St. Dev	1.03	1.02	0.97	1.40	0.99	1.45	1.03	0.99	0	1.40

The legally permissible maximum length for this type of trucks is 16.5m in almost all EU-member states including the four countries considered in this test. Since transport companies and vehicle manufacturers seek to optimise their vehicles within the legal boundaries it is expected that the average vehicle length will be close to 16.5m with a small variation. The mean lengths of the vehicles across all eight sites is within 1.5 metres which is encouraging and would allow the user to have some confidence in using the data for length and classification purposes.

Although individual vehicles may exceed this maximum value it is unlikely that the average value is higher than the maximum limit. This indicates that the length measurement of all sites is 0.11m less than expected yet it has a small variation. It is interesting to note that sites 7 and 8 exceed the maximum length for this type of vehicle but it is known that data from these two sites were likely to have anomalies due to lack of site maintenance and recent calibration. In all cases, this kind of structural measurement error can easily be compensated through calibration. Only site 6 shows a slightly higher variation but this could originate from the local traffic conditions.

4.4 Axle Distance

The tests on the axle distance between the 2nd and 3rd (driven) axles of 6 axle Tractor + Semi-trailer combinations has not been implemented due to difficulties with the limited detail in the vehicle classification in the data from a few of the sites. In other words it has not been possible to filter out this specific vehicle class needed for the test.

5. Procedures for Data Quality Management

5.1 Questionnaire

It is possible that the way users maintained and checked their systems may have an effect on the quality of the data. Therefore, it was decided to question the users about how their sites were used and how they were maintained. A questionnaire was developed containing 18 questions within 4 main headings, these were;

- General usage; what is the main use and specifications for your WIM data?
- Site Maintenance; what are the procedures for maintenance and calibration of the systems?
- Data Checks; what are the procedures for checking the collection of measurement data?
- Data Quality Control; what are the procedures for validation on the quality of the data?

The idea behind these questions was to try and ascertain the extent to which users maintain their sites and, in particular, the frequency in which they analyse and check the quality of the data obtained, i.e. procedures for quality control of their systems and data.

5.2 Results

In terms of general usage, there is a diverse spread between statistics, pre-selection and tolling. However, nearly all of the sites are maintained to the specifications laid down in COST323 although the strictness of individual users' interpretation of the specified procedures is highly variable. This is particularly noticeable when responses are analysed for the calibration methods and frequency.

From the responses received regarding site maintenance there appeared to be no direct correlation between site maintenance and data quality. As an example, the user who only calibrated every two years (the longest period) was not the worst performer in terms of quality whilst one of the users' who calibrated every six months had the worst performing sites. In fact one of the users' didn't have a regular site maintenance routine, although they calibrated every six months, and their data seemed acceptable from the tests carried out.

Regarding data checks; all of the respondents carried out data checks at regular intervals. All had routines whether manual or automatic that carried out these tests and were able to identify faults at reasonably short notice. The frequency at which the checks were performed varied from daily to monthly, surprisingly, the owner of the worst performing sites carried out their quality controls on a daily basis.

It is was interesting to see that all of the users employ robust, regular maintenance and quality control of their data but it has shown the tests we have developed can bring into question the reliability of some of the quality controls employed. However, it should be stressed that the sites chosen for this paper were random and may well have been known to the users that some of them had reliability issues prior to our examination of the data.

6. Conclusions

- A set of tests and criteria were developed and will allow users to make a quick verification of the quality of the data from any WIM system in Europe;
- However, it should be stressed, these tests are not an indication of the quality of the weights being produced by the WIM system;
- It is important to understand that these tests are purely meant as indicators into data quality without any prior knowledge of the location, status, calibration, capability or method of operation of the site;
- The tests look at the stability of different characteristics of the data measured by the WIM system;
- These results are specifically developed for the vehicle population of Europe but may be assessed for application elsewhere;
- These tests can be used to compare the relative quality of different WIM sites (the quality of the data from site A is better than that of site B);
- These tests can be used to give an indication of the quality of the data of a particular site (the data from site C has a quality that is sufficient);
- For this, criteria were developed to assess the absolute quality derived from the maximum legal limits for international goods transport and values common for certain types of trucks. The first four in the list below were selected for this study;
- The criteria are:

Criterion	Min. Value	Max. Value
Av. GVW of 3 axle rigid	15t	20t
Av. GVW of 5 axle articulated	25t	40t
Av. Steering Axle Load	6.5t	7.0t
Av. Vehicle Length	15.5m	17.5m
Av. Axle Distance	-	-
Variation in # of registrations	-	-
Percentage of unclassified	-	5%
Percentage of meas. errors	-	5%
# hours without registrations	-	5 per week

- The results from a questionnaire on procedures for data quality management by various users did not show a clear correlation between the procedures used and the quality of the data.

7. Recommendations

- Since the outcome of the test is sensitive to the choice of what week of data is used. The selected weeks should represent normal operational conditions. Weeks with known variations due to holidays, road works or extreme weather conditions should be avoided.
- In case of a negative result of these tests this should be interpreted as: “Do not use this data without additional checks on the quality of the data.”
- In case of a positive result this should be interpreted as: “There are no reasons to suspect the quality of this data however this is not a guarantee”;

- By repeating the tests on data of one system from a number of different weeks from different periods over a year, the results of the will give a more reliable indication of the actual performance of the system.
- A further investigation is needed on the relation between site maintenance, data quality procedures and the quality of the measured data based on a larger set of different WIM systems.

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Session 5 : Heavy Vehicle Impact on Infrastructures

Chair: Bernard Jacob (IFSTTAR, France)

ASSESSMENT OF EFFECT IN BRIDGE LOADING OF CHANGES IN TRAFFIC REGULATIONS

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Graduated from Ecole Polytechnique and Ecole Nationale des Ponts et Chaussées, has been working with SETRA, LCPC and Ifsttar in bridge engineering, heavy vehicle safety and regulation and WIM. Currently deputy scientific director with Ifsttar and president of ISWIM.

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Abstract

WIM data makes it possible to assess precisely the consequences of changes in the regulations on the weight and dimensions of the trucks in the impact on infrastructures. This is the case for impact on pavement (changes in the fatigue and rutting), on the compliance with geometrical constraints (geometry of the road and ability to drive on the existing infrastructure) and on bridge loading. We intend to present in this paper several studies on bridge loading based on WIM data and that have been conducted recently in France.
In a first study, the impact of the increase of the limit of 40t for GVW for 5 axle-trucks to 44t has been investigated. It has been shown that a decrease in lifetime of the structures should be expected (decrease by approximately 10%).
Another study has studied the effect of the changes in traffic between 1989 (when the European design codes for bridges have been written) and 2010. These changes have been shown with use of WIM data from 1989 and 2010: the traffic recorded in 2010 has effects beneath those induced by Load Model 1 of Eurocode 1 for bridges with spans higher than 20m, but the safety margin is reduced.
Keywords: WIM data, infrastructure, bridges, changes in weight and dimension regulation.

Résumé

Les données de trafic permettent d'estimer précisément les conséquences sur les infrastructures de changements dans la règlementation sur les poids et dimensions des poids lourds. Plus précisément, peuvent êtres estimer les conséquences sur la durée de vie des chaussées (fatigue, orniérage), la compatibilité avec les contraintes géométriques (géométrie de la route et capacité à manœuvrer dans les infrastructures existantes) et les charges sur les ponts. Nous nous proposons de présenter dans ce papier diverses études sur les charges de trafic sur les ouvrages d'art, réalisées ces dernières années en France à l'aide de données de trafic.
Dans une première étude, l'effet de l'augmentation du poids total en charge autorisé de 40t à 44t pour les véhicules à 5 essieux est étudié. Une diminution de la durée de vie des infrastructures a été démontré (diminution d'environ 10%).
Une autre étude s'est intéressée aux effets des changements de type de trafic entre 1989 (date de calibration de l'Eurocode 1) et 2010. Ces changements ont été analysés à l'aide de fichiers de trafic de 1989 et 2010 : il a été montré que le trafic de 2010 a des effets inférieurs à ceux du modèle de charge LM1 de l'Eurocode 1, mais la marge de sécurité a diminué.
Mots-clés: Données de trafic, infrastructure, ponts, changements dans la règlementation des poids et dimensions des poids lourds.

1. Introduction

When one needs to study the interaction between traffic and infrastructure, there is the possibility to use the load models given in the standards. For example, in Eurocode 1, several load models are given for various goals. The drawback is that these models have been derived on few years in the past (even a few decades in the past) with one given set of WIM data and with integration of safety margins.
Therefore, if local and up-to-date WIM data is available, it is valuable to perform the same calculations but with this real traffic data. This has been done in the two studies we present here.
The first study deals with the consequences on bridges of the increase of GVW limit in France from 40t to 44t. WIM data with GVW limit of 40t has been chosen and modified in order to take into account an increase of this limit to 44t. For both traffic files (recorded one and modified one), the impact on bridges has been assessed.
In the second study, infrastructure designed according to load models of Eurocode 1 is assessed for current traffic. To achieve that, traffic data files of 1989 (used for calibration of Eurocode 1) and of 2010 have been applied to bridge structures and the consequences in extreme loads and in fatigue lifetime have been compared.

2. Consequence of change in regulation of weight and dimension of trucks

In a first study, the impact of the increase of the limit of 40t for GVW for 5 axle-trucks to 44t has been investigated: for that, recorded data has been modified based on some simple assumptions, like the one that a given proportion of the trucks loaded near the 40t-limit would see their weight shift by 10%. Then, the new traffic data file has been used to assess the impact of this new traffic on several bridge types. We explain here the new traffic regulations, the original used WIM data and how this WIM data has been modified to take into account the new regulations.

2.1 Weight limits in French legislation

In France and in Europe for international transport, the standard gross vehicle weight limit is 40 tons. Some countries allow higher weights, such as 44 tons in the UK for 6-axle articulated trucks. In France, there are a couple of derogations which allow 44 tons for 5-axle articulated trucks if:

- 40 ft containers are transported in a multi-modal journey,
- the freight comes from or goes to a maritime or inland harbor, where it is carried by ship,
- some specified agricultural goods are transported during specific seasons. Moreover, log trucks are allowed up to 48 tons on 5 axles and 57 tons on 6 axles by decree.
- Since this study, 44t have been allowed for 5-axle trucks on national journeys and if all axle loads are below 12t.

In 2008, the French parliament voted a law called “Grenelle de l’environnement” to reduce the CO_2 emissions and the fossil energy consumption. An article stated that road transport regulation shall be adapted for that. In February 2009, the parliament asked to the government to study the positive and negative impacts of increasing the gross weight limit to 44 tons. The main criteria to consider were road safety, CO_2 emission and energy consumption, traffic congestion, and infrastructure (bridges and pavement...) lifetime and maintenance.

For bridges, the first task was to compare the effects of a single 44 t truck to those of a 40 t truck. Because the axle load limit would not be increased, only medium span (15 to 40 m) bridges could be affected, or 10 m continuous span bridge for bending moment on pier. Shorter spans could not support a whole truck at once. Longer spans are not so much sensitive to a single truck. For medium span bridges, the load effects would be increased by less than 10%, which is not too much critical for the extreme loads and load effects on healthy bridges. However, the impact of multiple presences (truck crossing or overtaking) of 44 t trucks, or the effect on the fatigue lifetime was to be investigated more in depth.

2.2 WIM data

Traffic data and loads are collected in France for bridge engineering by WIM systems since the early 1980's. However, with the recent development of a national WIM network for overload screening and enforcement (Marchadour & Jacob 2008), more reliable and accurate data are collected continuously on the main highways and motorways. The traffic data used in this study were collected on two adjacent traffic lanes of the French motorway A9 near Montpellier in South France, over a month in June 2009. Figure 1 shows the gross vehicle weight distributions on the slow lane over one and two weeks.

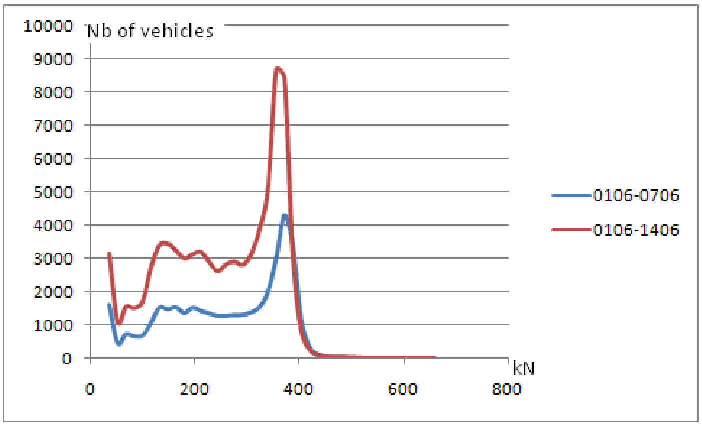

Figure 1: Gross weight distributions on the slow lane of the A9 motorway, 1 & 2 weeks in June 2009.

Axle loads and spacing, speed and time of passage in 1/100 s are also recorded for each truck in both lanes. The accuracy of these data are at least in class C(15), but mostly in class B(10) of the European specifications of WIM (Jacob et al. 2002), i.e. app. 95% of the gross weights are within ±10% and of axle loads within ±15% of the static values taken as the reference.

2.3 Modification of WIM data: Updating traffic load effect model with consideration of traffic evolution

This original WIM data has been modified, as to take into account the new traffic regulations. Several ways to update the WIM data have been reported in the literature.

2.3.1 Traffic volume increase

A crucial assumption in modeling lifetime traffic load effects for design is the stationarity of traffic. However, the increase of traffic has been widely reported in the literature. Indeed the increase of traffic volume may impact bridges. Gindy & Nassif (2007) have stated that the traffic volume (or truck volume) has the same significant effect on the frequency of multiple truck presence as bridge span length. The increase of probability of occurrence of multiple-truck-loading event will lead to larger load effects on bridges, and it will threaten the safety of bridges. A linear truck traffic growth model has been widely used to predict future truck traffic (Lu et al. 2007). Based on known information, the annual average daily truck traffic at age t can be predicted by:

$$AADTT_t = AADTT_{BY} + AADTT_{REF} \cdot GR \cdot (t - t_{REF})$$

where GR is the traffic growth rate in percentage, $AADTT_{BY}$ and $AADTT_{REF}$ are the annual average daily truck traffic during the recorded year (used as the basis) and the reference year, respectively. Usually, the base year equals the reference year.

2.3.2 Traffic composition

Not only included by the growth of traffic, the propriety of non-stationarity of traffic can arise from the variation of traffic composition. Observations from various countries have demonstrated that the composition of truck traffic has changed dramatically in recent decades, especially for heavy truck. As shown in Figure 2, the composition of traffic has hugely changed between 1986 and 2010, for traffic measured at two WIM sites in France: the proportion of 5-axle trucks has increased by about 30%, while the proportion of 4-axle truck has decreased by about 20%. This may be caused by the change in regulations during this period, namely the increase in gross vehicle weight limit from 36 to 40t in 1992. 4-axle tandem trucks were replaced by 5-axle tridem trucks. As a matter of fact, the truck industry always tries to always reach the weight limit of traffic, which may significantly change the vehicle proportions travelling on roads.

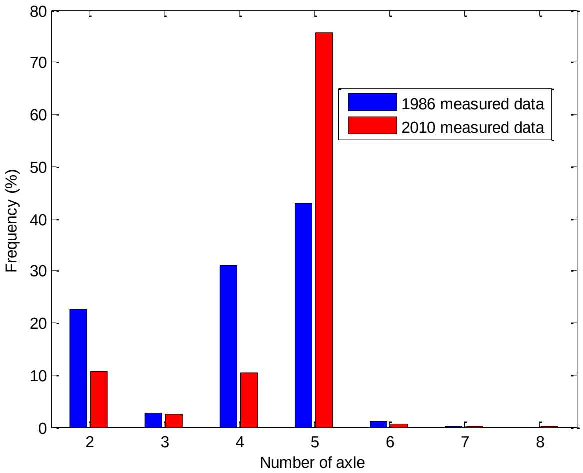

Figure 2: Evolution of the proportion of the vehicule types (classified according to the number of axles)

2.3.3 Truck weight limit change

Due to the limited land resource and traffic safety considerations, the current road network cannot afford continuous increase of traffic volume. If no modal shift is achieved, longer and heavier trucks may be therefore needed to transport freight as it can reduce the traffic volume and also decrease energy consumption (de Ceuster et al. 2008). Allowing these longer and heavier trucks traveling on the road would require changing the current truck weight limit.

However, this change in truck weight limit may threaten the safety of existing highway infrastructures like bridges. For instance, Cohen et al. (2003) has reported that an increase in truck weight limit would cause significant life reduction due to fatigue. The truck weight limit change may cause a series of changes including GVW, axle weight, traffic composition, and also leads to introduce new types of trucks.

Many different approaches have been developed to predict such changes in distribution of truck weights. In this paper, the method which predicts the distribution through the histogram of measured truck weights, developed by Cohen et al. (2003) has been adopted. Their approach considers changes in the truck weight histogram due to three types of freight shifting: the truck load shift without change in truck types, the truck load shift with a change of truck configuration, and the exogenous shift from e.g. economy growth.

In this study, only the first type of freight shifting has been considered, because a potential proposal of change in the weight limit is to allow a 5-axle truck load 44 tons maximum against current 40 tons in France (General Council of Environment and Sustainable Development, 2011).

2.3.4 Methodology used in the presented study

The very simple and crude assumptions done here are:

1. the gross weight of every heavy vehicle laying between 36 and 44 tons would be increased by 10%, the additional weight being uniformly distributed on all axes;
2. all the other vehicles would have the same load as before (volume limitation or not enough freight to carry).

With these assumptions, a micro-simulation generated a “modified” traffic file named “44 t” derived from the natural traffic record of the WIM system on the A9 motorway, named “40 t”.

Both traffics were used with influence lines, to obtain the effects and their histograms.

2.4 Comparison of the traffic load effects depending on the weight limit

The effects of traffic on a bridge are usually calculated by applying traffic loads, either measured by WIM systems or simulated by software, on influence lines or surfaces. For local effects sensitive to the wheel transverse location, WIM data shall contain this information and an accurate influence surface, i.e. a two-dimensional calculation, must be used. For most of the global or semi-global and longitudinal effects, such as bending moments at mid-span or on pier, shear forces or pier reactions, one or a set of parallel longitudinal influence lines (one per traffic lane) are sufficient, and the traffic data lane by lane are used. That is the case in this study.

The influence lines or surfaces are obtained numerically, through 1-D bridge model or 2-D finite elements calculations, or on site through experimentation (by strain measurement on a bridge under a known truck). In this later case, several parameters are taken into account, such as the stiffness of the pavement surface, sidewalks and safety barriers, which are neglected in the numerical method.

The effects considered in this study are, for two bridges:

- The bending moment stress at mid-span of a simple supported 40 m span bridge, near Auxerre. This is a composite bridge with two main steel girders and a concrete deck.
- The bending moment stress at mid-spans and on piers of the Libourne 4-span bridge (respectively 48, 60, 60 and 48 meters-long). This is also a 2-steel girder composite bridge.

These influence lines are given in MPa/MN in Figure 3.

The original WIM data and the updated one have been applied to these bridge load effects with the computer software POLLUX developed in the LCPC/Ifsttar. The traffic load effects by these two traffic have then been compared. This makes it possible to assess the consequences for such a change.

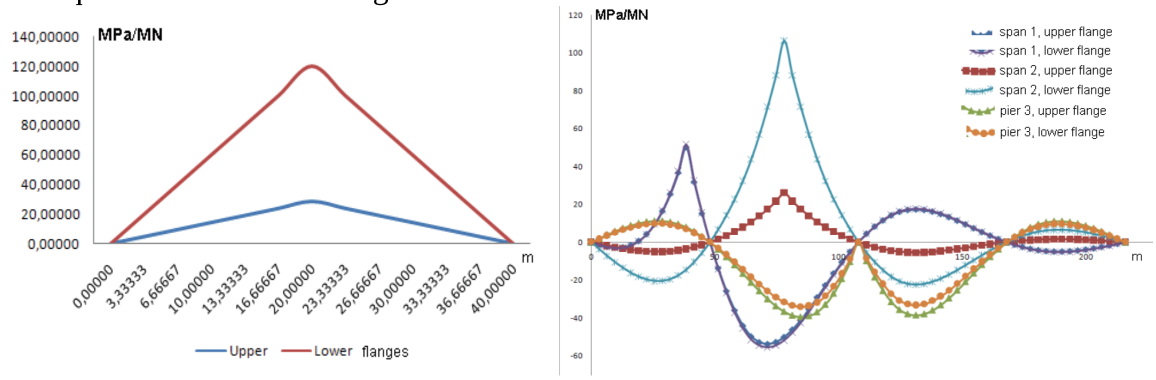

Figure 3: On the left, influence lines of Auxerre composite bridge. On the right, influence lines of Libourne bridge.

2.5 Conclusions of this first study

The increase of the extreme stresses was limited to 6.5 or 8.5%, on a 40 m simple supported span (bending moment at mid span effect), carrying three traffic lanes. The multiple presence of more than one truck in adjacent lanes and the passage of exceptional or overloaded trucks explain that this increase is less than 10% (40 to 44 t).
The computed lifetimes in fatigue for both bridges are rather short, because the real traffics on these bridges are local traffics and much lighter than the motorway A9 one. However, the reduction of the lifetime, whatever the fatigue resistance (S-N class) and the bridge, is close to 20%.

Since this study, the traffic regulation is France has indeed changed: the limit of GVW for internal traffic has been increased from 40t to 44t for trucks whose axle loads do not exceed 12t. For the others (internal traffic with axle loads between 12t and 13t, and international traffic), the limit of 40t for GVW still stands.

3. Consequence of change in traffic

The second study that is presented here deals with the evolution of traffic effects between the time when bridge codes have been calibrated (Eurocode 1, end of the 1980's) and today.

3.1 Issue

The currently used normal load model, LM1, in Eurocode 1, Part 2 was first calibrated with a two weeks heavy traffic dataset from Auxerre (A6 motorway, Paris to Lyon, France) in the late 1980s; it was then re-calibrated by O'Connor et al (1998) with several representative European traffic datasets recorded at France weigh-in-motion (WIM) sites. The increasing traffic load effect has been found as the augmentation of traffic flow and probability of multiple trucks on bridge simultaneous. Therefore, the load model needs to be periodically re-assessed by current traffic, because of the wide changes in traffic volume, composition of traffic, vehicle weights and sizes, to ensure a satisfactory safety level for the design of new bridges; and also the quality of WIM data has increased greatly in the last decade due to improved technologies and the development of specifications regulating accuracy levels. Accurate prediction of load effects expected during the proposed or remaining lifetime of a structure is a key issue for the design or assessment of highway bridges.

3.2 WIM data

For this study two sets of WIM data are studied to extrapolate the extreme value of GVW and traffic load effect on a given bridge. One was recorded in the 1986, and the other consists of modern data that was recorded in 2010. In order to eliminate possible measurement errors, these data were cleaned before processing with cleaning rules (Sivakumar et al., 2010; Getachew 2003; Enright 2010), such as GVW greater than 3.5t, vehicle speed in the range of 35 km/h to 160 km/h, etc.

The first set was recorded by the same WIM station on A6 highway at Auxerre in France, and this site has 4 lanes of traffic (2 in each direction). However, two lanes were recorded for one week from 26th May to 2nd June 1986. It contains 46049 trucks after filtration. The second set of data was from a piezo-ceramic weigh-in-motion system on the A9 motorway near Saint Jean de Védas, South-East of France in 2010. Only the upstream traffic lanes are recorded. In total 835468 trucks from January 2010 to May 2010 (GVW greater than 3.5 t) were recorded in the three lanes, with an average daily truck flow of 6217 trucks.

Tables 1 and 2 show the traffic remarkably evolved from 1986 to 2010. The average daily truck traffic (ADTT) has more than doubled in these 24 years; the average yearly growth rate is about 4.5% that is larger than the average growth rate of 2.7%. The composition of traffic has also hugely changed as shown in Figure 3, the proportion of 5-axle truck increases by about 30%, while the proportion of 4-axle truck decreases by about 20%, it is caused by an increase in the gross vehicle weight limit from 36 to 40t in 1992. 4-axle tandem trucks were replaced by 5-axle tridem trucks.

Table 1: Comparison between the to traffic data sets

Name of road	A6	A9
Time of recording	May, 1986	Jan. – May, 2010
Site location	Auxerre	St Jean-de-Vedas
No. of measured lane	2	3
Record period (days)	7	138
No. of trucks recorded	46049	835468
Av. hourly flow per lane	107	259
Av. daily flow per lane	2558	6217

Table 2: Comparison of vehicles types (according to the number of axles)

No. of axles	A6, 1986		A9, 2010	
	No. of trucks	Percent (%)	No. of trucks	Percent (%)
4	14306	31.07	82926	9.93
5	19835	43.07	628709	75.25

These two data sets have been applied to the same bridges structures and the extreme loads experienced with these two traffics have been compared to the extreme effects induced by Load Model 1 (LM1) of Eurocode 1. The details on the structural assessments can be found in (Zhou et al, 2012) and (Zhou et al, 2014).

The conclusions are the following: when comparing the effect of these two traffic files with the effect of the load model 1 of Eurocode 1, two cases can be distinguished, namely spans under 30 meters and spans over 30 meters. For spans smaller than 30 meters the effect of current traffic is higher than the effect of the traffic recorded in 1986. For spans longer than

30 meters, in which the governing case is the congested traffic, the extrapolated value of 1986 is higher than the extrapolated effect of the actual traffic. This is due to higher scattering of the “old” traffic data.

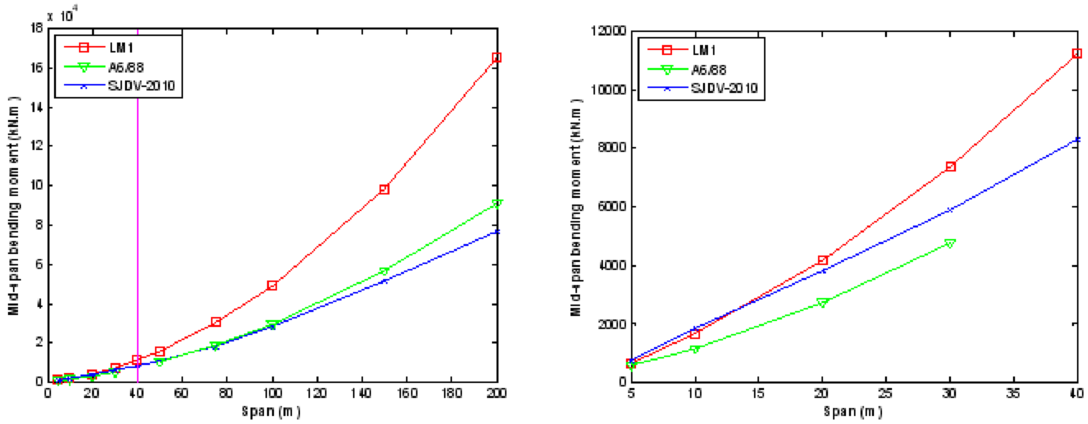

Figure 4: Extreme mid-span bending moment for simply supported bridges of various span lengths, according to various methods (the graph on the right is a part of the left one, highlighting the spans between 5 meters and 40 meters).

In all cases, it may be found that the effect induced by the load model 1 of Eurocode 1 is higher than the effect of the measured traffic. The safety margin is reduced. But one issue remains to be solved: which dynamic amplification factor should be applied (Gonzàlez et al, 2008)? Indeed, there is already some dynamic amplification included among the errors of the WIM data, but it is low and has no link with the dynamic amplification due to vehicle-bridge interaction.

4. Conclusions

Bridge code calibration as well as assessment or re-assessment of existing bridges under traffic loads require an accurate knowledge of the load patterns. WIM data are very useful for these applications, either to give an account of the current traffic loads or to forecast the potential impact of future loads.

It is then necessary to determinate which kind of infrastructure is the most sensitive to this change of traffic (for example for bridges, the type of structure, number of spans, their lengths). This infrastructure has therefore to be assessed.

Several points are still open nowadays, and research is dedicated to them. In order to give two examples, one can cite the cleaning of WIM data and the dynamic amplification. AS for the cleaning of the data, the issue is to remove false recordings. But how to discriminate an error from a “normal” recording”? Then, WIM data already contains some dynamic amplification, but it is not similar to that observed when a vehicle crosses a bridge. Therefore, how to eliminate the WIM dynamic amplification and add an structural dynamic amplification?

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PAVEMENT DAMAGE – BRAZILIAN ROAD DETERIORATION TEST USING WIM





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Abstract
This work aims to study the pavement deterioration in real conditions by doing pavement assessment, using both information from pavement instrumentation and multiple sensors weigh in motion to define a pavement deterioration model. The analysis model principle uses the accumulated damage caused by the traffic load. It considers the traffic load spectra, speed and pavement temperature, as the influence in pavement stiffness modulus and fatigue law. In the field, a data acquisition system provides strain and stress information of the pavement structure. WIM systems provides information about the heavyweight vehicles on the experimental track. The sensors are install in groups of sixteen rows spaced in one meter between each line. The study found that for any increase on the load above the legal limit diminish pavement life.

Keywords: Pavement, Pavement Damage, Pavement Deterioration, Heavy Vehicles, Weigh-in-Motion, WIM.

Resumo
Este trabalho tem como objetivo o estudo da deterioração de pavimento em condições reis por meio da avaliação do pavimento, usando ambas informações de instrumentação de pavimento e sistema de pesagem em movimento usando múltiplos sensores para definir uma modelo de deterioração de pavimento. O princípio do modelo de analise utiliza o dano acumulado causado pelo carregamento do tráfego. Considera a espectro de carregamento, velocidade e temperatura do pavimento, como fator de influência no módulo de rigidez e na lei de fadiga do pavimento. Em campo, um sistema de aquisição de dados provém as informações de tensão e deformação da estrutura do pavimento. Um sistema WIM provém as informações dos veículos de carga na pista experimental. Os sensores são instalados em grupos de dezesseis linhas com espaçamento de um metro entre cada linha. O estudo apresenta como resultado que o aumento acima do limite legal contribui para a redução da vida útil dos pavimentos.

Palavra-chave: Pavimento, Dano em pavimento, Deterioração de pavimento, Veículos pesados, Pesagem em movimento, WIM.

1. Introduction

The high-speed multiple sensors weigh in motion has been under research by several international organisms and countries. For Brazil, as for most of the nations, the weigh in motions systems are an important tool to perform weight enforcement directly on the highway. This project is inserted in a broader study called the High-speed Multiple Sensors Weigh in Motion Systems and Pavement Mechanical Analysis. This project was born due to DNIT (National Department of Infrastructure and Transportation) needs to perform weight control in the National Weighing Plan. Then, an agreement between DNIT and UFSC (Federal University of Santa Catarina) was done to elaborate and define MS/WIM procedures. In Brazil, these new technologies have potential to perform statistics data collection, overload pre-selection and, in the future, for direct enforcement. One of the most important contribution for WIM development and used as reference for this research is the COST 323 research (COST 323, 1998).

A pavement structure is design to resist a certain number of cycles of loading. The life span of this structure will depend only in the amount of loading of each vehicle. On the roads, pavement is constant submitted to distribution of loadings. The pavement life duration reduces as the number of vehicles overloaded increase.

The Weigh-in-Motion systems allow us to estimate the resultant force on each vehicle axle. Additionally, it has great potential to increase the efficiency and effectiveness of control overloading practices, which is in charge of the authorities responsible for road operations. This work aims to study the pavement deterioration in real conditions by doing pavement assessment, using both information from pavement instrumentation and multiple sensors weigh in motion to define a pavement deterioration model.

2. Damage analysis model

The analysis model is based on the accumulated damage caused by the traffic load. This model considers the traffic load spectra (load per axle or axle group), speed and pavement temperature, as the influence in pavement stiffness modulus and fatigue law. A numerical viscoelastic pavement software, such as ViscoRoute (Chabot et al., 2009), calculates the equivalent strains and stress for each load, which is dependent on the load speed and pavement temperature. The strains calculated to each load is than associated whit the frequency that appears at the load spectra. The strain frequency spectrum shows the distribution of deformation applied on the pavement due to passing traffic combined to pavement characteristics (a composition of load and speed). The pavement fatigue curve allows to access the strain ε value that represent the pavement lifetime N. The value N represent the number of cycles of loading on pavement structure. The fatigue curve can connect the pavement lifetime, in this analysis in years, with the amount of load applied.

The damage calculus is a function of the load (C), velocity (V) and temperature (T) as shown in equation (1). The damage is cumulative sum of damages over the life of the pavement that breaks when the value D is equal to one. In the equation n is the cumulative traffic load summary over pavement lifetime and N is the number of loading accumulated that leads to the end of pavement life, accordingly to a certain amount of deformations.

$$D = \sum_k^C \sum_i^V \sum_j^T \frac{n_{ijk}}{N_{ijk}} * 100 \qquad (1)$$

3. Field analysis

In the field, a data acquisition system provides strain and stress information of the pavement structure. The recorded data correspond to the pavement structural layer behaviors as well as the dynamic force from the free flow traffic. In laboratory, material form the tests site allow to determine mechanical characteristics of material, mainly by the fatigue test and complex modulus determination, both performed in the Pavement Laboratory at Federal University of Santa Catarina, UFSC.

For this project, a 700-meter-long experimental track was built, located in BR-101 highway, km 418, near Araranguá city, Santa Catarina state, Brazil. The cross section is composed of a semi-infinite sand subgrade, 20 cm Macadam layer, 18 cm graded gravel layer and 17 cm of Hot Mix Asphalt layer. It was designed to be the Weigh Station main entrance, presented in Figure 1.

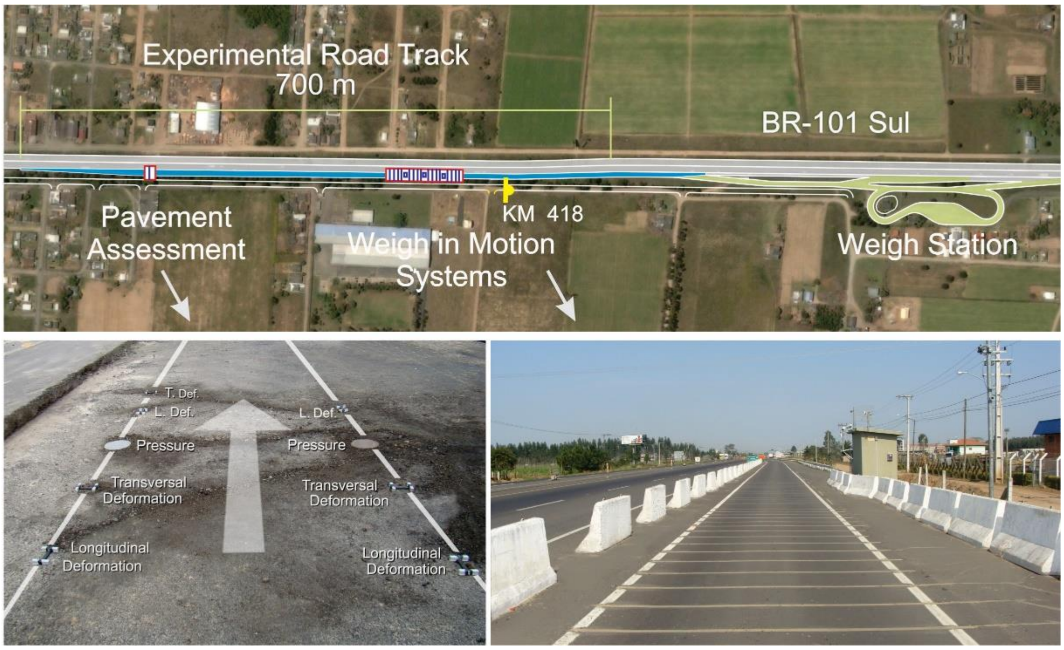


Figure 1 – This is a sample figure caption

4. Pavement deterioration analysis

The pavement structure fatigue process has origin in the repeated interactions between the tire and the pavement. The pavement material behavior, allied with external factors as solicitation and physic conditions, allow understanding of deterioration mechanical process of the pavement. The pavement strain and stress assessment shows the intensity of the efforts applied. It can be used to evaluate the pavement support parameters. Pavement design aims to obtain an appropriate behavior during lifetime, besides, to ensure safety and comfort to the road users. This process considers the load applied over time, the deformation found in the bottom of surface course and the stress found in the top of subgrade.

The pavement assessment system uses devices under and over pavement surface, which allow the acquisition of information for the identification and quantification of pavement behavior under certain conditions of temperature and humidity. A set of sensors are installed in a way that allow identify the deformation under asphalt layer, base layer and sub-base, in longitudinal and transverse alignments. Likewise, pressure on top of the base layer, sub-base and subgrade. Moisture of granular layers and temperature at three depths in the asphalt concrete are measure at same time as the others measures. The longitudinal transversal strains, in the bottom of the layers, are monitored by strain gauge specially designed for this function.

The vehicle weighing data derives from the weigh-in-motion system. The weigh-in motion sensors are installed in rows in transversal aliment to the direction of the traffic. The technologies used are piezoelectric quartz, piezoelectric ceramic, piezoelectric polymer and fiber-optic sensors.

WIM systems provides information about the heavyweight vehicles on the experimental track. The sensors are install in groups of sixteen rows spaced in one meter between each line. The data of the weighing system are organized by date and time, which is recorded when a vehicle met the first sensor. Each event contains information of the vehicle class, axle numbers and space between them, axle weight, gross weight and speed.

The deterioration of pavements analysis uses both measurements of pavement assessment system and weigh-in-motion system together with material characteristics defined in laboratory. The sensors installed in the pavement structure informs the pavement behavior in the moment that one vehicle passes by. As vehicle pass over the experimental track, the WIM system identifies and measures the axle weight.

Viscoelastic software input parameters, resented by Chabot et al. (2009), are the pavement material characteristics determined in the laboratory and field. The material characteristics defined in laboratory are complex modulus and fatigue curve. These two characteristics, mainly fatigue, governs the structural behavior of the pavement during the lifetime span. The pavement structure is assessed applying both traffic information from WIM system data collection and data traffic from the weigh station.

The alternated bending test machine accesses asphalt mechanical characteristics. This equipment allows determining the complex modulus and the fatigue characteristics in different conditions of temperature and load frequency. The results of complex modulus determination give a linear viscoelastic characteristics of the asphalt material, because they are measured in the field of small deformations.

All viscoelastic materials responds relatively to the tension applied by a with a delay. In the field of small deformations, the small sinusoidal force results also in a sinusoidal response. Thus, the deformation presents a phase shift in relation to the force, which reflects the material behavior. When the phase shift is equal to 0º, it means that the material is purely elastic. When phase shift is equal to 90º, it means that the material is purely viscous. The modulus of the complex |E*| can be express by equation (2):

$$|E^*| = (E_1^2 + E_2^2)^{\frac{1}{2}} \tag{2}$$

The different components of the complex modulus vary with temperature and frequency. The experimental results |E*|, φ, E1 and E2 are expressed by graphical representation called: Isotherme, equivalent frequency, Isochrone, Cole-Cole and Black space. E1 represents the real part, or elastic part, and E2 the imaginary part, or viscoelastic part. The specimen is a block with dimensions h_{layer}(17cm) x 60cm x 40cm removed from de asphalt course. From it, trapezoidal specimens are made to perform complex modulus and fatigue tests in the two point bending machine.

The Cole-Cole representation provides the parameters for the Huet-Sayegh model (Huet, 1963), which provides parameter for pavement design, Table 1, calculated with aid of Viscoanalyse (Chailleux, 2009). The model is obtained by a spring of stiffness E_0, which represents the elastic modulus. The model is given by Equation (3):

$$E^*(i\omega\tau) = \frac{(E_0+(E_\infty - E_0))}{1+\delta\,(i\omega\tau)^{-k} + (i\omega\tau)^{-h}} \tag{3}$$

Table 1 – The Huet-Sayegh parameters

E_0	E_{inf}	δ	k	H	τ	$A0$	$A1$	$A2$
53	13304	0.573	0.132	0.518	0.065	1.405	-0.295	0.0013

Figure 2 shows the comparative of complex modulus between two different years representation the asphalt mixture from the experimental road track.

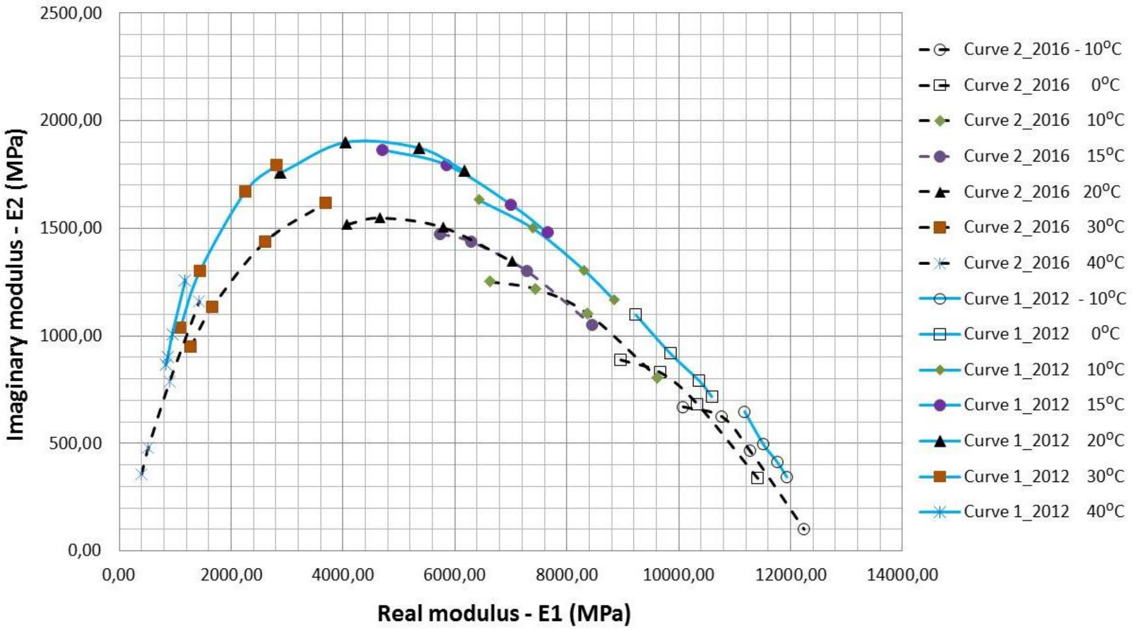


Figure 2 – Comparative Cole-Cole curve

The fatigue test is performed in continuous mode and controlled deformation, thus the stiffness of the specimen decreases as the number of deformations applied increases. The results must be around the 10^6 numbers of alternated deformations, in two point bending test. The test aims to found a deformation corresponded to one million cycles applied, called ε_6. The criteria adopted are the same as recommended by French fatigue test method, executed at 10ºC and 25 Hz.

The fatigue curve which accompanies deterioration of the pavement 2012 and 2016 are presented in the Figure 3. The curve represents the susceptibility of asphalt mixture to deformation effort, represented in scale log-log. The abscissa is the deformation, in 10^{-6} m, and the ordinate is the accumulate number of deformation cycles. The curve is a line represented by an exponential equation, which curve inclination is the exponent. The equations of the year fatigue curves 2012 and 2016 are:

$$\mathrm{N} = 1.22 * 10^{16} * \varepsilon^{-5.10} \qquad 2012 \tag{4}$$
$$\mathrm{N} = 1.17 * 10^{15} * \varepsilon^{-4.60} \qquad 2016 \tag{5}$$

The deformation specific result of fatigue test result is the deformation for 10^6 cycles. From equations (4) and (5) are determined to deformation for 10^6 cycles, for the year 2012 and 2016. The found values of deformation ε_6 are 95.024 μm and 94.998 μm respectively. N represents the number of axels accumulated on the pavement over the years, in other words, the sum of loads, which will pass by the road section during the pavement lifetime. Therefore, the equation enables comparing the deformation found in field with the fatigue curve to establish the deterioration degree.

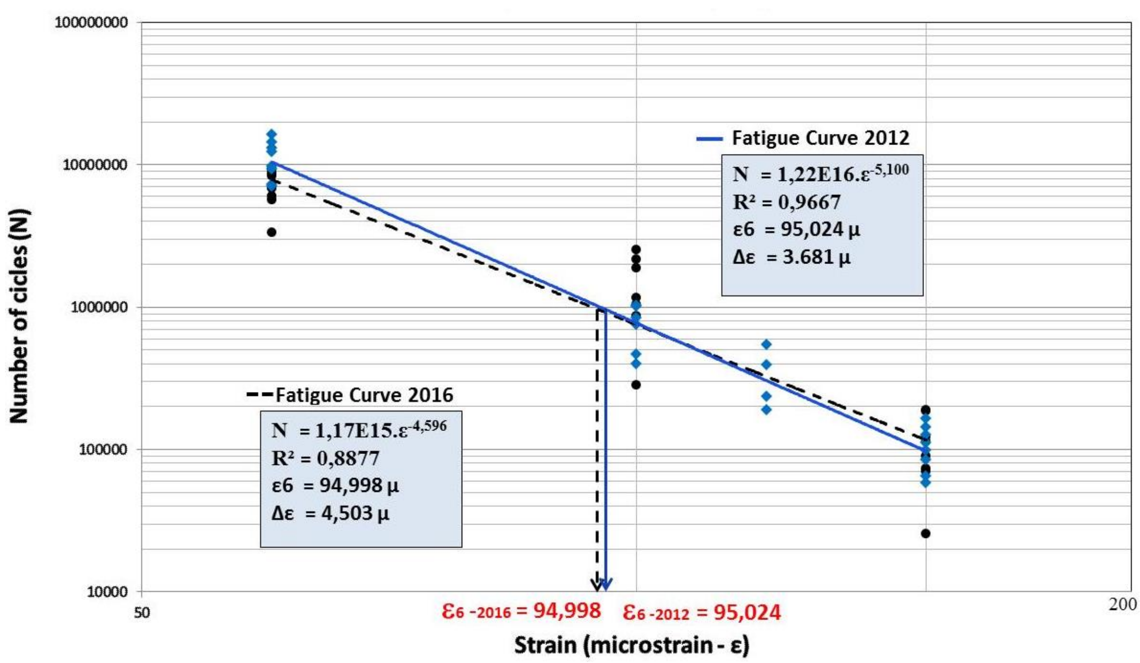


Figure 3 – Comparative curve of fatigue (temperature= 10ºC e frequency=25Hz)

5. Damage analysis

Mainly there are four types of axes: single axle single wheel, single axle dual tire, tandem axle, tridem axle. Vehicle fleet have its specific axle composition and, for each axle type, there is a respective load distribution. The loads in field obey a normal distribution, with the most common value near legal limit and other values below or above the expected value. Figure 4 shows the load spectra for the three most influent types of axles and their legal limits (describe in the Brazilian legislation).

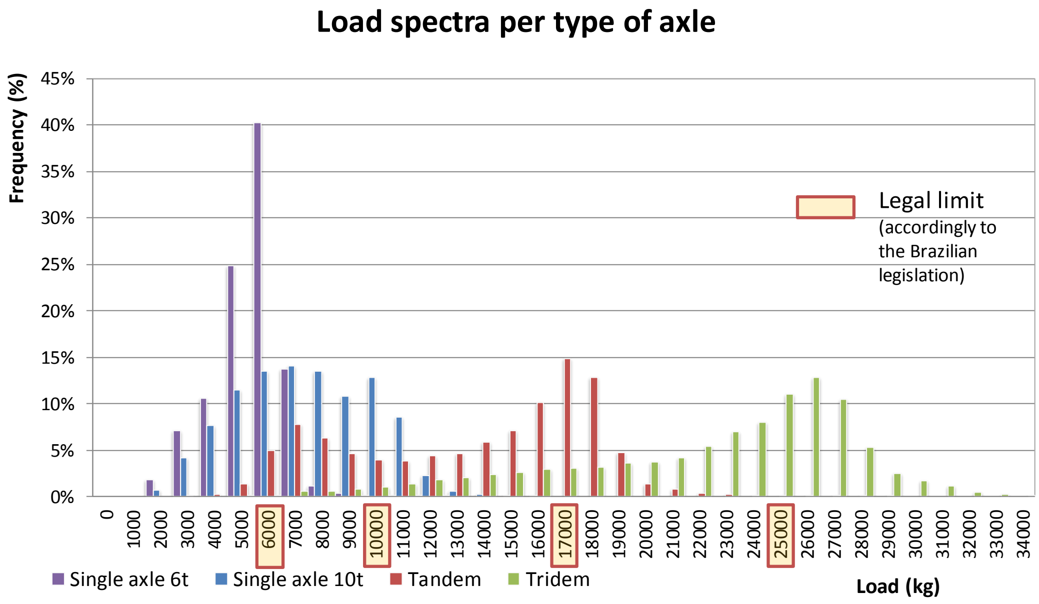


Figure 4 – This is a sample figure caption

All parameters are organized and loaded into the analysis software together with pavement structural characteristics. Among all results, the pavement longitudinal deformation is the behaviour observed. This value then can be linked directly to the deformation found in the fatigue curve. The design information used for simulation of the traffic and the behaviour of the pavement are:

- traffic open year 2011;
- project period of 15 years, 2026;
- characteristics of asphalt concrete (Model rheological Huet-Sayegh);
- characteristics of the base BG, sub-base and subgrade MS;
- axle types: single axle dual tire, tandem and tridem;
- actual average temperature of the pavement (z = 17cm): 22 ° C;
- Speed: 80km/h e 60km/h.

Table 2 - Pavement physical and statistical parameters

	Parameters	Value (2012)	Value (2016)
Complex modulus	|E*| (10°C; 10Hz) - Mpa	8418	8446
	|E*| (10°C; 25Hz) - Mpa	8801	9355
Fatigue	|E*| (15°C; 10Hz) - Mpa	7186	7404
	ε_6 (10^6)	95.024	94,998
Coefficient	Fatigue slope	-5.1	-4,6
	Kr	1.0	1.0
	Kc	1.1	1.1
	Ks	1.0	1.0

Axle interaction simulation Table 2 contains the physical and statistical parameters, used in the pavement numerical simulation. The coefficients kr, kc and ks corrects the deformation ε6 from the fatigue test and then becomes working strain at the base of the bituminous layer, define both in 2012 and 2016.

5.1

Two simulations can present how pavement life is related to load and velocity variations. The analysis uses the correspondent strain considering a fleet of hundred per cent of single axel, a hundred per cent of tandem axle and a hundred per cent of tridem axle. Table 3 presents the result from traffic and pavement life interaction, considering increasing the load, starting from legal limit, and vehicle velocity variation. On this simulation, the modulus and fatigue adopted are from the material extract in 2012, at the moment of construction.

Table 3 - Pavement end of life proportional to load increase and velocity variation

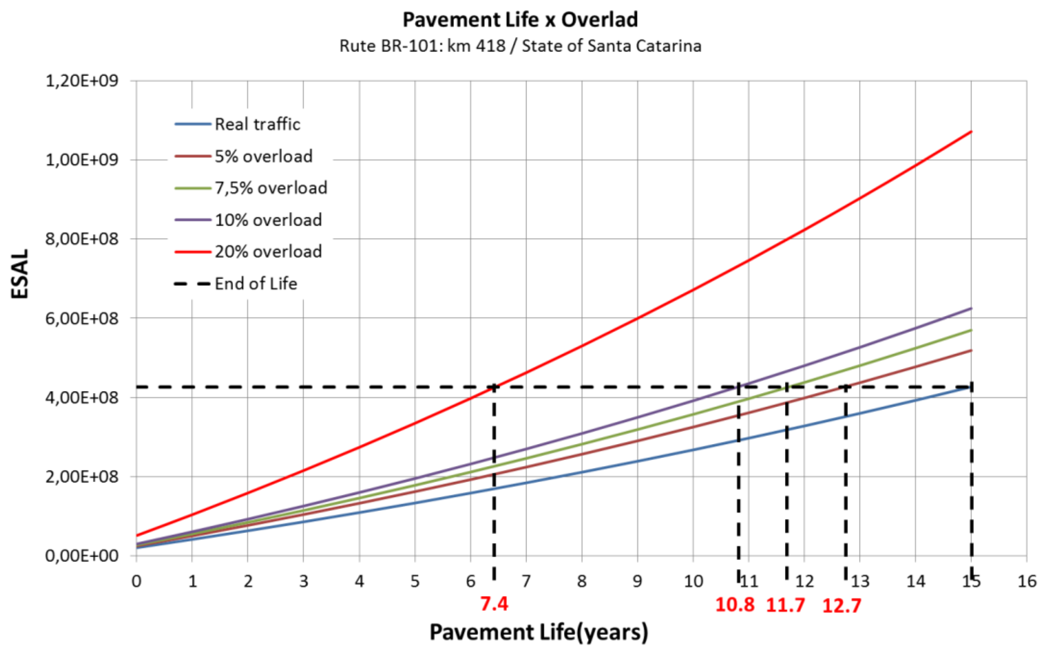
Axle	Load (t)	εt (obtained) (10^{-6}) Load speed 80km/h	εt (obtained) (10^{-6}) Load speed 60km/h	End of life in years after traffic opening 80 km/h	End of life in years after traffic opening 60 km/h
Single axle	8.2	49.9	51.0	15	12
	10	60.8	62.1	2	2
	10.5 (5 %)	63.8	65.2	-	-
	10.75 (7.5 %)	65.4	66.8	-	-
Tandem axle	17	49.7	50.9	15	12
	17.85 (5 %)	52.2	53.5	11	9
	19.19 (7.5 %)	56.1	57.5	6	5
Tridem axle	25	48.3	49.6	15	12
	26.25 (5 %)	50.8	52.0	12	12
	28.22 (7.5 %)	54.6	55.9	8	6

The study found that for any increase on the load above the legal limit diminish pavement life. In addition, velocity variation has an important effect on the damage caused on pavement structure, the lower velocities the bigger the damage. An analysis considering wide range of velocity and load shows how important load speed is to pavement life.

5.2 Real traffic composition interaction

Consider an entire fleet of vehicle composed by a hundred percent of traffic with a specific load is too radical, but indicates how important an overload of a specific axle is comparing to others. As we can see in the Figure 5, even when we consider a real traffic data and an increase of 5, 7.5, 10 and 20% of overload.

If all vehicle starts to carries more than 5% of overload, the pavement life reduces in 15%, if it carries more than 7.5% of overload, the pavement life reduces in 22%. If carries more than 10 and 20% of overload, the life is reducing in 28 and 50%, respectively.



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6. Conclusion

It can be assuring that any increase on the load over the axles is the major problem for pavement performance and consequently contributes to reduce pavement life. These phenomena can be observed in the first analysis. The analysis of fatigue curve and complex modulus curve shows the deterioration of the pavement was increase along the time. Comparing the two fatigue curves, year 2012 and 2016, it shows reduction of the working strain of 10^6 cycles, also reduction of the complex modulus, presented at Cole-Cole curve. Mainly these two changes in the bituminous concrete are related to natural aging process. According to the material viscoelastic behaviour law, faster the load is applied harder the material behaves. As shown in the results, as lower de the vehicle speed shorter the pavement lifespan is. The real traffic composition shows the increase of overload and pavement life reduction, it is clear that 20% of overload can reduce pavement life in approximately 50%.

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Session 6 : Overload Enforcement

Chair: Hans van Loo (Corner Stone International, The Netherlands)

FRENCH POLICY TO PREVENT OVERLOADING

   

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Abstract

In this paper, the policy aspects of overloadings enforcement is presented. First, the regulations part of the paper, which is based on the French highway code dealing with the overloadings, will be detailed as well as the French overload penalty system. Next, we will detail the equipment used to record overloadings offenses, and the organization needed to run the overloadings controls. Finally, we present the national project called 'direct enforcement of overloading by WIM', which was launched by the French Ministry of Transport in 2014.

Keywords: Heavy vehicules, Freight transport, Weigh-in-Motion (WIM), enforcement, french regulation, european regulation.

Résumé

Dans cet article, la politique de la répression des surcharges est présentée. Tout d'abord, la partie 'réglementation' qui reprend le code de route français relative aux surcharges sera détaillée ainsi que le régime des sanctions correspondant. Ensuite, nous détaillerons les matériels utilisés pour constater les infractions liées aux surcharges, ainsi que l'organisation nécessaire au fonctionnement de l'activité du contrôle des surcharges. Enfin, nous présenterons le projet CSA surcharge, pour lequel le ministère français en charge des transports est maître d'ouvrage.

Mots-clés: poids lourds, transport de marchandises, pesage en marche, répression, réglementation française, réglementation européenne.

1. Figures on HGV traffic

The General Directorate for the Infrastructure, Tranport and the Sea (DGITM) is in charge of the implementation and enforcement of the legislation for road transport. The enforcement of weights and dimensions of heavy goods vehicles (HGVs) is part of its mission.

In France, in 2014, there were 551,000 HGVs, and 92,000 busses for intercity passenger transport. 84.9% (in ton-kilometres) of goods transport was done by road, and 36.7% of this amount was done by foreign companies. About 64% of the HGVs operate in transit only.

The Department of Transport detects and enforces overloaded HGVs for three main reasons:

• Road safety: HGVs represent about 6 % of the vehicle km, about 3% of the vehicles implicated in accidents with injuries, and abour 9% of the vehicles implicated in accidents with fatalities. However, about 14 % of the fatalities are caused by an accident in which a truck is involved (but not always responsible!).
• Fair competition between hauler companies and transport modes. A 5-axle articulated truck with a 20% gross weight overload gets an additional benefit of 26 500 € per year.
• Road safety and infrastructure durability. A 10% overload on a 13 ton axle means a damage increase of about 60% for a flexible pavement and about 100% for a rigid pavement. The fatigue damage of bridges also quickly increases with the truck loads (Jacob and Labry, 2002).
The maximum single axle load allowed in France (13 tons) is higher than in most of the other EU member countries, but the legal gross weight is 40 tons for a 5-axle articulated truck, as in the EC96/3 directive.

About 5 to 10% of the heavy good vehicles (HGV's) are overloaded and some trucks are overloaded by 20% or more.

2. HGV's Weight Legislationand penalties

The French driving law (Legifrance, 2000) contains 5 rules on HGVs' weight limitations:

• R312-2: the gross vehicle weight, or any axle load, cannot exceed the maximum specified on the vehicle registration document;

• R312-3: the trailer weight cannot exceed 130% of the tractor weight, and up to 150% for a combination of more than 32 tons;

• R312-4: the maximum gross weight is 19, 26 or 32 tons for 2-, 3-, or 4-axle single trucks, and 38 or 40 tons for 4- or 5- and more-axle articulated trucks.

As from 1st January 2013, the Decree of 4th December 2012 allows road haulage vehicles with more than 4 axles to run with a gross weight between 40 and 44 t on the french national territory. This authorization is applicable to every type of goods, without any restriction. This authorization is framed by a set of technical requirements that shall be observed, in particular strict limitations for the axles load of the tractor and the trailer and also Euro standards (cf R312-5 and R312-6);

• R312-5: the maximum single axle load is 13 tons. In the case of road haulage vehicles with more than 4 axles running with a gross weight between 40 and 44 t, the maximum single axle load of the tractor is 12 tons;

• R312-6: a tandem axle cannot exceed 14.7 to 21 tons, and a tridem axle cannot exceed 22.5 to 31.5 tons, depending on the axle spacing, with no more than 7.35 to 10.5 tons per axle belonging to the group (there are some exception for driving tandem axles). In the case of road haulage vehicles having more than 4 axles run with a gross weight between 40 and 44 t, the maximum allowed load of the trailor tridem is 27 tons.

In 2011, the French overload penalty system was revised and reinforced to be more dissuasive (decree N 2011-368 of April 04th, 2011). Fines are now applicable by step of 1,000 kg for gross weight above the legal limit, and by step of 300 kg for axle load. Vehicle more than 5% above the legal limit may be stopped and downloaded, but mostly that is applied to overload of 10% and more.

Thus, a vehicle with a gross weight 46,4 tons for a vehicle having a maximum permissible gross train weight of 38 tons is punished by 8 fines of 4th class, to which are added the possible penalties concerning the gross vehicle weight and the axle loads. For 8 fines, the infringement cost is 8*90 = 720 euros.

If the level of overloading on the gross weight is over 5% above the legal limit, the truck is stopped and the driver can be asked to downlooad the extra load. Usually, the extra good are picked up by another truck sent by the transport company. The extra cost of all these operations is charged to the transport company. The transport company is liable for overloading ... but the stakeholder can also be responsible in certain case.

3. Organization of the overloading controls in France

3.1 Human ressources

Road transport enforcement in France are mainly performed by the control officers (from the ministry of transport), the police and Gendarmerie from the home office (Ministère de l’intérieur) or the customs officers (controls of goods carried by vehicles).

The General Directorate for Infrastructure, Transport and Sea (DGITM) of the French Ministry of Transport appointed at about 500 controls officers who are spreaded out over 19 regional directorate for environment, planning and housing (DREAL : Direction Régionale de l’Environnement de l’Aménagement et du Logement). One of their task is to fine trucks overloadings.

3.2 Tools used to enforce truck overloadings

3.2.1 Static and low-speed scales

Overloaded trucks are enforced using static or low-speed scales since these devices are approved from the national metrology authority in order to be used for enforcement purpose.

500 statics scales (mobile and fixed) and 3 low speed *weighing* systems are available in France.

Vehicule are picked up from the traffic by the police. There are oftenly 2 controls officers and one or two policeman in a static weighint control area.

Mobile axle weighing system are used in two way :

- in temporay weiging site : it is necessary to use a roll-up ramps wich support the axle scale, in order to avoid load transfert between the axle of group et so to minimize the measurement errors. The ramps are portable and available in multiple lengths, comprised of either aluminum or wood or or steel. Haenni and Captels weighin scales are used.

Figure 1: Captels static weighing scales

Figure 2: Haenni static weighing scales

- in permanent site wich are specially equipped roadside areas : we use the weighing system installed in concrete pavement, on a concrete slab of 30 m in length and 4.5 m in width, with mobile weighing scales provived by Captels. The advandage of this system is that it can be installed and removed to another site.

Fixed axle weighing system are installed, on motorway, and these system are provided by Precia.

Figure 3 : Precia fixed axle weighing system

In addition, 3 low speed weighing sites are used by the DREAL. These sites are equipped with low speed weigh in motion system which can be operated until 8 km/h. They are provided by Captels and used in combinaision with HS wim system.

All the static weighing systems respect the OIML R-76 requirements for III and IIII classes.

According to OIML R76 requirements, it is necessary, yearly, to perfom periodic – verifications and in-service inspections on the weighing instruments, otherwise the weighin scale must not be used for endorcement purpose. The maintenance and the managment of the 500 weighing scales is a full time job for 2 technicians.

Static weighings are time consumming and need a lot of human ressources like policemen and control officers on the control area. An average of 25 trucks can be checked in a 2 hours control session. Thus a small percentage of the trafic flow is monitored. The overloadings of 50,000 truks are controlled every year in France usins statics scales.

In 1995, the DGITM (former DTT) appointed IFSTTAR (former LCPC) to carry out studies about using low speed weigh-in-motion (LS-WIM) systems for enforcement purpose; this was achieved in 2000 and a LS-WIM system was type approved by the Legal Metrology in 2004, and is now in operation on 3 checking area. LS-WIM overcomes several disadvantages of static weighing, such as interception of HGV's, long operation of weighing axle by axle, extensive staff resource required.

3.2.2 High speed weigh in motion

In 2004, the Minister of Transport aannounced the development of a HS-WIM network capable to detect and to preselect overloading. A European call for tenders was issued in 2006, won by the French company Sterela. In 2015, 29 WIM sites are in operation all around France, mainly located on long-distance corridors and near the borders (see figure 4). The aim of this network is monitoring the HGV's flow, focusing on the overloaded HGVs. The HS-WIM systems are mainly used by the regional control teams (DREAL) in two manners:

- in real time, to select HGVs looking as as overloaded and to direct them on a check point for a double check on an approved scale. Overloaded vehicles are then fined and downloaded if necessary. With this, 96% of HGVs stopped are overloaded. Moreover, over speeding HGVs indicate a possible violation on its speed limiter.
- the data gathered 24 hours a day all around the years are used to monitor overloads on the equipped itineraries. Frequently law-breaking companies are identified and warned by letters. The data are also used identifying the days and hours with most overloading, to target the controls in these time periods.

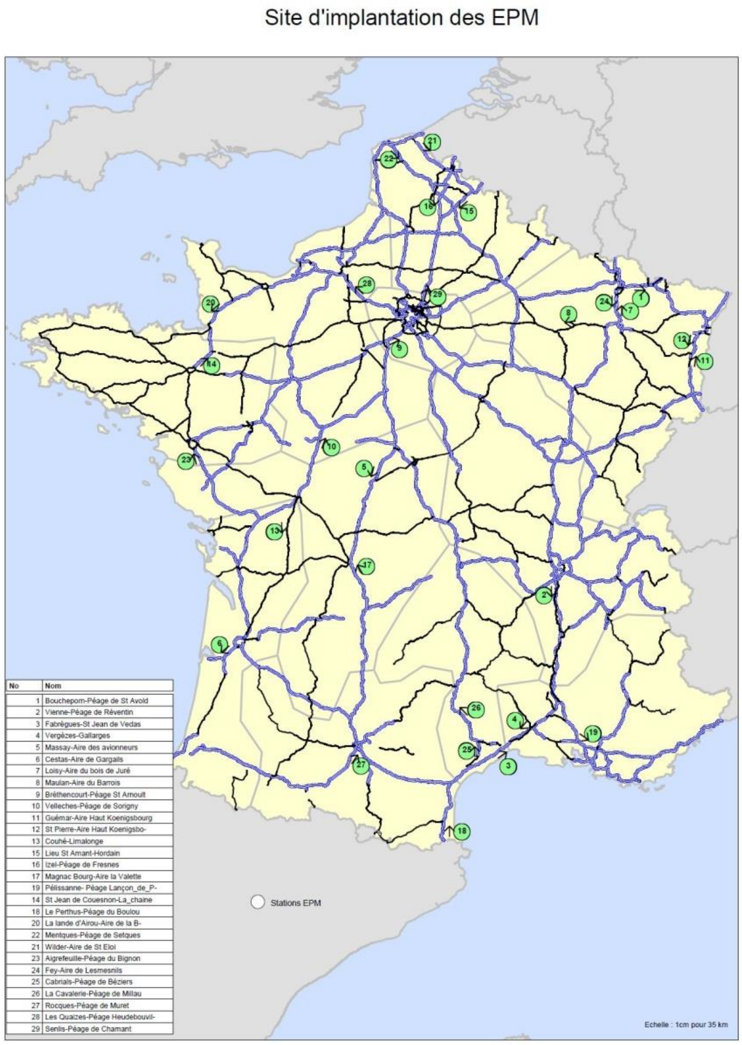

Figure 4 : **The HS wim sites network**

Each site is made of three equipments:

- the WIM equipment (WIM-E), made of a WIM station, a video camera, and communication tools. In order to to enhance the WIM accuracy and to allow an efficient pre-selection, WIM piezoquartz sensors are used for more accurate speed measurement, which is directly used for weight calculation and the wheel lateral positioning in the traffic lane is monitored in order to get rid of measurements on the sensor edges (see figure 5);

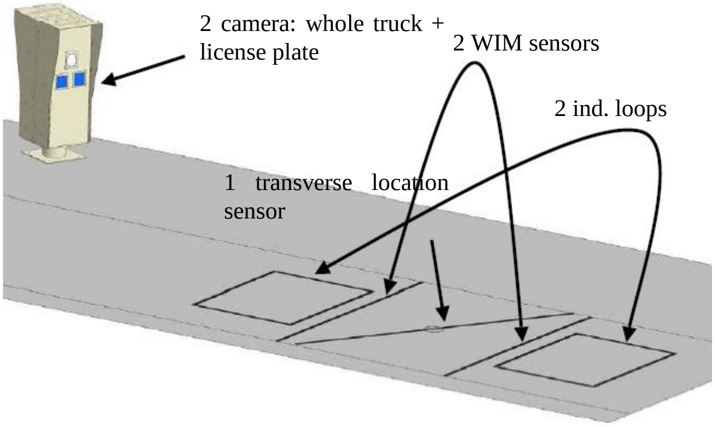

Figure 5 : Image of a suspected overloaded truck

- the Module of Mean Speed measurement (MMS), is located more of 1 km away of the WIM-E on the same traffic lane or the same direction. It determines the average speed of a lorry over the distance between both equipments, using the two times of passage and the registration plate number ;
- the Static Control Weighing Area (SCWA), receives images (see figure 6) and parameters of the suspected heavy vehicles to be controlled. It is equipped with static or low-speed scales installed on a parking lot, a toll area, etc.

7 technicians, from Cerema and Sterela, are needed for the maintenance of the HS wim network.

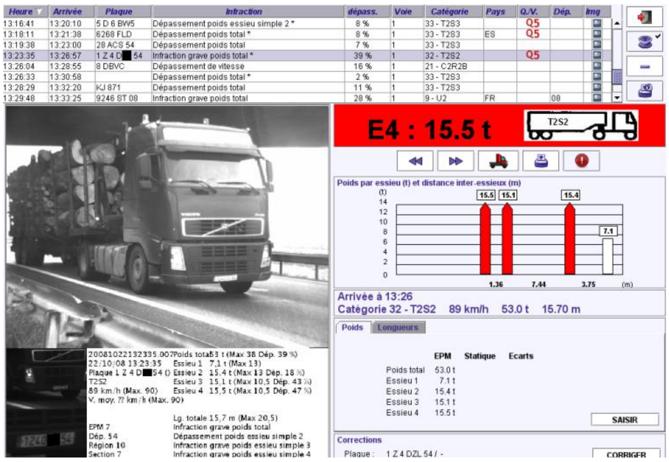

Figure 6 : Image of a suspected overloaded truck

Yearly, the characteristics (axle loads, speed, silhouette, axle spacing, total vhechicle length) of 120 millions of vehicles, including 23 millions of trucks, are recorded by the HS WIM french network.

4. Toward a direct enforcement wim system

Direct enforcement of overloadings is one solution for making more dissuassive the static controls of trucks, as in the same the part of trucks traffic is growing year after year.

Thus, In 2013, the DGITM launched a new WIM project, led by IFSTTAR and involving Cerema, to investigate the feasibility of using HS-WIM systems for direct enforcement in a legal metrology frame.

This is a very ambitious objective since it is necessary to obtaine approval from the national metrology authority to certify that this type of WIM is able to be used for enforcement purpose.

This 4 year project consists in 2 phases:

(1) phase 1 in 2014-15 to demonstrate the feasibility of type approval by OIML a HS-WIM system for direct enforcement;

(2) phase 2 in 2016-17 to build and test prototypes.~~,~~

The project consist of 4 work package (WP).

WP1 aims at deploying procedures for type approval and certification of systems for future direct enforcement system, in connection with legal metrology and LNE (National Metrology Laboratory). One major output of this WP is to describe the experiment plan for type approval.

WP2 is divided in two parts:

- the WP2.1 deals with sensor/pavement interactions studies and aims to characterize their response in laboratory and on road in controlled conditions. One output of this WP is to design corrective law depending of the pavemanent and behaviour characteristics.
- the WP2.2 aims at developing a new accurate and cheap optical fibre sensor wich could be used for WIM applications.

WP3 is about the use of multiple sensor (MS-)WIM for direct enforcement. It consits of designing an optimal arrays, data processing tools in order to reach the willing tolerances for direct enforcement.
WP4 id dealing with bridge (B-)WIM system and to study how to use this technology for direct enforcement.
WP EXP deals with road trials, data collection and data analysis.

The projet is divided in 5 work packages which all focuse to WP1 (Feasability and type model approval), WP 2 (signal and sensors behaviours Optic fibers), WP3 (Vehicule dynamics corrections and sorting) and WP4 (Bridge Weigh in motion).
The total budget of the project is about 2000 k€.

Another issue which needs to be addressed is to identify the true legal limit of each individual HGV by HS-WIM systems or with coupled additional sensors. The evolution of weight regulation leads to more complex rules, such as 40 or 44 t gross weight limit for 5-axle articulated trucks depending on their operation mode (e.g. multimodal container operation) or on the current legislation, or special allowances for specific goods, e.g. log trucks in France up to 48 or 57 t on 5- or 6-axle articulated trucks. WIM systems becomes now part of an integrated intelligent transport system (ITS).

5. Conclusions

Since the 60’s, the policy makers are aware of the impacts of overloading on traffic safety, on damages for infrastructure and on unfair competition between transport companies and transport modes.

The efficiency of statics controls is improved by using HS wim system, since the preselection is proved to be very accurate.

Because traffic trucks increases year after year, more trucks have to be controlled and so direct enforcement is the solution to make dissuassive the overloading for all the traffic truck. That is why, the succes of the french direct enforcement projet is crucial for the French Ministry of Transport

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THE CONTROL ON OVERLOADED VEHICLES AND AUTOMATIC AXLE WEIGHING SYSTEM FOR RAPID TRANSIT INSTALLED IN THE HANSHIN EXPRESSWAY



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Abstract
The Hanshin Expressway has a network in the Kansai urban area of Japan. With improving the efficiency of freight transportation systems and the size and weight of commerce vehicles, it is obviously increasing overloaded vehicles. There are two ways to detect overload vehicles. Police Force and We cooperate to stop vehicles and to measure vehicle static loads. In another way, Automatic Axle Weighing System at the toll gates is monitoring of axle loads of vehicles and shooting photos at the tool gates. Since ETC system installed to toll gates, vehicles are running through the toll gate in 30km/h speed limit. Then we installed “the High-Precision Automatic Axle Weighing System” to detect the axle load of running vehicles. However, this system costs very high. It should be able to detect the axle load of running vehicles with lower cost than High-Precision Automatic Axle Weighing System.

Keywords: the High-Precision Automatic Axle Weighing System, Axle overloading vehicles, Crackdown, Piezoelectric quartz sensor, Maintenance.

Résumé
L'Autoroute Hanshin a un réseau dans la zone urbaine de Kansai du Japon. Avec l'amélioration de l'efficacité de systèmes de transport de marchandises et la grandeur et poids de véhicules de commerce, il augmente évidemment des véhicules surchargés. Il y a deux façons de découvrir des véhicules de surcharge. La Police et Nous coopérons pour arrêter des véhicules et mesurer le véhicule les charges statiques. D'une autre façon, le Système de Pesant d'Axe Automatique aux portes de péage surveille des charges d'axe de véhicules et tire des photos sur les portes d'outil. Depuis ETC. le système installé pour sonner des portes, les véhicules parcourent la porte de péage dans la limitation de vitesse 30km/h. Nous avons installé "la Haute Précision le Système de Pesant d'Axe Automatique" pour découvrir la charge d'axe de véhicules courants. Cependant, ce système coûte très haut. Il devrait être capable de découvrir la charge d'axe de véhicules courants avec le prix inférieur que la Haute Précision le Système de Pesant d'Axe Automatique

Mots-clés: la Haute Précision Système de Pesant d'Axe Automatique, véhicules de surcharge d'Axe, Répression, détecteur de quartz Piézoélectrique, Entretien.

1. About the Hanshin Expressway

With a network of 259km in service, Hanshin Expressway is a Japanese leading urban expressway operator, serving major Kansai urban area: Osaka, Kobe and Kyoto. The great deal of expertise surely contributes to the future development of the areas since 1964. Figure 1 shows the Hanshin Expressway Network.

Figure 1 the Hanshin Expressway Network

Road networks expand over the Kansai urban area of Japan. The total road length reached 3933km. Hanshin Expressway Co., Ltd. operates 6.0% of the road network in Kansai urban area Japan. Average daily traffic volume is about 740thousand in 2013 and about 63thousand of them are large vehicles. And 50% of these large vehicles use the Hanshin Expressway.

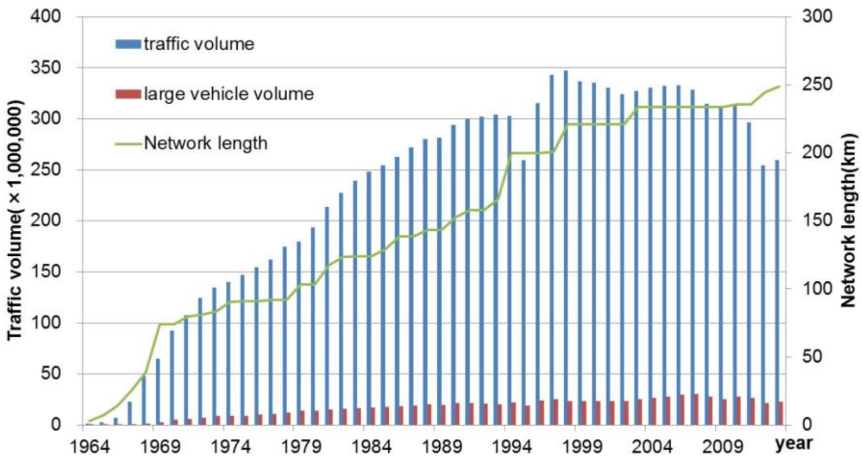


Figure 2 Traffic volume and Networks length

Hanshin Expressway Co., Ltd. has started to operate Distance-Based Toll Rate System in January 2012, and traffic count system also has been changed. However, the traffic volume was not changed as before.

Hanshin Expressway Co., Ltd. controls and operates a network of 259km in total and over 200km of it are highway bridges. Current improving efficiency of freight transportation and enlarge of vehicle size. The essential task of the Hanshin Expressway are prevention of extensive damage to road structures, mitigation of noise and vibration caused by overloaded heavy trucks. Japanese vehicle weight limit is 25t and an axle load limit is 10t.

The vehicle over 20t axle loads running has same effect on the road bridge structures as done by about 4000 vehicles of 10t axle loads running. Then, axle overloading vehicles are highly likely to violate the weight limit.

2. Transition of number of vehicles with axle loads violation

Number of large vehicles passing through the Hanshin Expressway increased to 30 million by 2007. Then the number decreased to 23 million by 2013. Since the Hanshin Expressway has started to operate Distance-Based Toll Rate System in January of 2012, volume of large vehicles running on the expressway seemed to fall. But the number of heavy vehicles stayed still in fact. The count of overloaded axles has been increasing since Axle Weighing System was installed in 1981. The number reached 1.4milion axles in 1986.

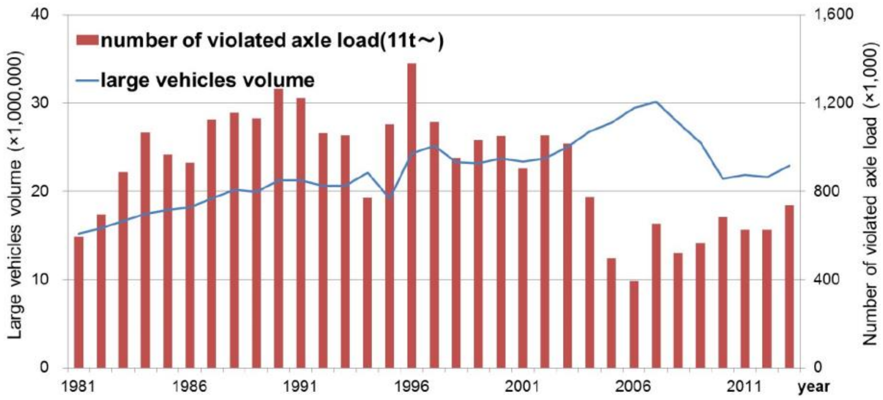


Figure 3 Volumes of large vehicles and Number of violated axle load

However, the axle weighing system before 2008 could detect total number of axles loaded over 11t for stating violation tendency but it was not able to count number of vehicles with overweight axles. Since 2004, commercial traffic industries had made an effort to reduce illegally overweight vehicles, the Hanshin Expressway records 0.6milion overloaded axles in average. But the record should be awareness still high.

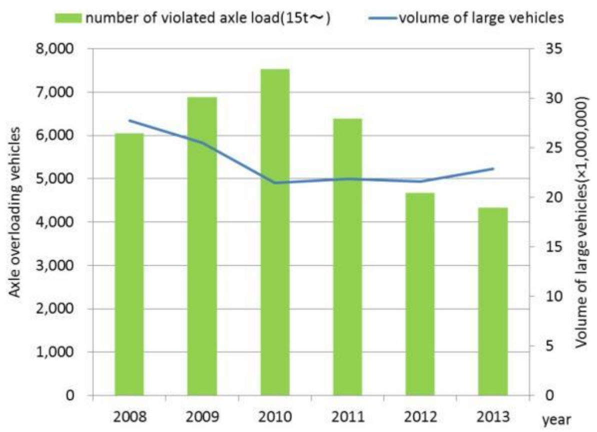


Figure 4 Volume of large vehicles and Axle overloading vehicles

The Hanshin Expressway has been implementing ETC (Electronic Toll Collection System) at toll gates since 2001. Along with that installation, High Precision Automatic axle weighing system has been developed and utilized from 2008. This advanced axle weighing system became available to detect accurate axle loads of single vehicle in 2010 this high precision automatic axle weighing system has been utilized, the number of intentional violators of axle loads weighing over 15ton tends to reduce.

3. Crackdown effort on violation of the Vehicles Restriction Ordinance

3.1 Damage by violation of the Vehicles Restriction Ordinance

“Recommendation of heavy traffic evaluation for aging roads” was enforced by Ministry of Land, Infrastructure, Transport and Tourism in 2014. Axle overloading vehicles rates 0.3%.
The 0.3% violated vehicles consume 90% of damage impact on road bridge functions. The axle overweighing traffics leads increase traffic noise and vibration, traffic congestion and accident risks.
Social and economic growth demands more commerce by in change of truck size, higher load efficiency. Hanshin Expressway Co., Ltd. complementary liberalizes large commercial motor vehicle regulation and the procedure of permission for appropriate truck owners to facilitate highway functions. It is also still needed to crackdown on illegal overloaded vehicles and to accuse the malicious violators.

3.2 Automatic detection with fixed axle weighing system

There are 370 toll gates lanes in total on the Hanshin Expressway. There are 248lanes with fixed axle weighing system. The ETC system became widely used from 2001. The axle load weighing system was required to measure vehicles running through ETC gate, and then a high precision automatic axle weighing system has been developed. This advanced system has been deployed currently over 138lanes to sense violated axle load in motion automatically. The 99% of large vehicles are passing through ETC gate in these days. The system became available to perceive 90% of overweighing trucks.

Photo 1 High-Precision Automatic Axle Weighing System at toll gate

Hanshin Expressway Co., Ltd. shows warning message sign of overweight loads to offenders at toll gate and shoots pictures to identify responsible parties or offenders.
Hanshin Expressway Co., Ltd. enforces the repeat violators to participate in Anti-Violation of the Vehicles Restriction Ordinance seminar held by the Police enforcement and transportation authorities once in a year.
The records of violators are sent to the Police enforcement and Transportation Authorities regularly. In 2013, 600 warning letters were sent to offenders out of 2400 overloaded vehicles.
Hanshin Expressway Co., Ltd. and related authorities coordinate the possibilities to prosecute against repeat offenders or responsible parties of overweight freights.

3.3 Crackdown against overloading at toll gate

The Traffic Control Unit sets schedules to supervise on overloading every weekday, one time for each morning and afternoon period. The Unit was put in total 544 days for the duty in 2013 in Osaka and Hyogo area.
Automatic detection system records dynamic loads of vehicles. The data are available to only use for reference because offenders of weight limit do not commit their violations at the time.
The Traffic Control Unit can catch violators at toll gates and make them commit their illegal facts of total weight and axle loading, vehicle size, unpermitted special motor vehicles or unauthorized loads against Road Act. The Unit has the duty to prevent illegal overweighing vehicles running on the highway.
A Suspected driver is told to pull over at "instruction stations" near toll gates, where vehicle weights (gross weight, axle weight) and sizes (length, height, width) are measured, and check its special vehicle permission. Receiving message on violation of axel load sign from axle loading system at toll gate, the vehicle is weighed using portable axle loading equipment. The equipment scales its static load of the vehicle and calculates gross weight.
The traffic operation authorities designate roads to allow vehicles with 25t of maximum gross weight due to maximum axle span and 4.1m of maximum height. If the vehicle exceeds the size or weight regulation, Hanshin Expressway Co., Ltd. As being the operation authority of the expressway issues an Instructive Order by the law to responsible parties or the driver of violated vehicle, and commands the vehicle out of the expressway from nearest exit. In another case, an Instructive Warning is issued to the offender in slight grade of violation.

4. Axle weighing systems in the Hanshin Expressway

Conventional axle weighing systems were composed of a plate form sensor, a processing unit, a photo device and a display. The systems in 1980s were weighing static vehicles at toll gates. When ETC systems are widely using, High-Precision Automatic Axle Weighing System comes after. The system is additionally set up two devices to former systems that are bar shaped sensors weighing in dynamic mode and a vehicle detector dividing axle loads into each vehicle.
However, each device of High-Precision Automatic Axle Weighing System costs very expense and takes long hours for maintenance. These were reasons to innovate another advanced weighing system in dynamic mode.

Table 1 specification of axle weighing systems

	Conventional System	High-Precision Automatic Axle Weighing System	New Axle Weighing System
Weighing sensor	Plate type	Plate + bar shape	Piezoelectric quartz
Photo device	Film	Digital	Digital
Vehicle detector	Nothing	Existence	Existence
Dynamic mode	Up to 20km/h	Up to 40km/h	5 to 40km/h
Installation flexibility	Fair	Not good	Good
Cost per lane	13mil yen	20mil yen	15mil yen

4.1 Conventional System

Conventional axle weighing system has four components. These are a plate type sensor, a processing unit, a photo device and a warning message display.

The plate type sensor is weighing vehicles. The sensor is wider than wheel tread width. A strain gage load cell is in the plate type sensor. Strain gauge resists against weight on wheels in motion. The sensor scales the axle loads from changing resistance of the strain gage. The processing unit is set in the toll booth. When the sensor detects overloads, the processing unit transmits signals to photo device to shoot pictures of the violator and to display warning message on the display. The photo device is using film camera. The film is collected periodically.

4.2 High-Precision Automatic Axle Weighing System

High-Precision Automatic Axle Weighing System is additionally set up bar shape sensors and a vehicle detector into the conventional system.
The bar shape sensors are narrower than wheel tread width. Multiple strain gages are installed in the bar shape sensors. The strain gages scale axle load. Two bar shape sensors make possible to measure passing speed of vehicles and accurate weighing axle load in motion. This innovation gets more accuracy of axle loads of a vehicle than before. The system could detect axle load in static and dynamic mode at speed 0 to 40km/h.

Vehicle detector is using a laser to separate each vehicle. The detector retrieves passing each vehicle’s signals and processing unit outputs its signals to weighing axle load sensor.
Weighing sensor defines axle loads of each vehicle. Detecting violation axle load, the processing unit transmits signals to automobile classification device in ETC system and to a photo device to shoot photos of the violating vehicle. This photo device uses digital camera. It is available to see the picture by remote control. Figure 5 shows comparison between Conventional system and High-Precision Automatic Axle Weighing System.

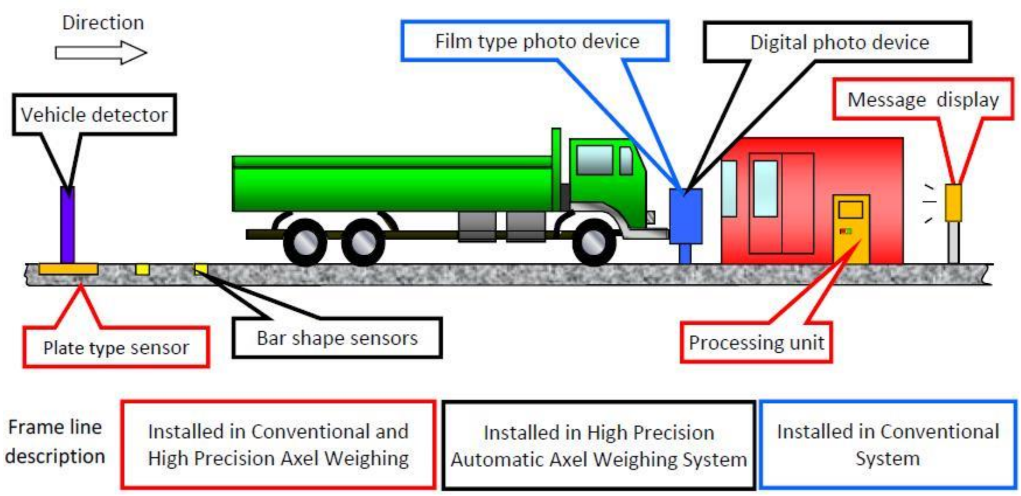


Figure 5 Conventional system and High-Precision Automatic Axle Weighing System

4.3 New axle weighing system

Figure 6 shows comparison between High-Precision Automatic Axle Weighing System and New axle weighing system with piezoelectric quartz sensors.

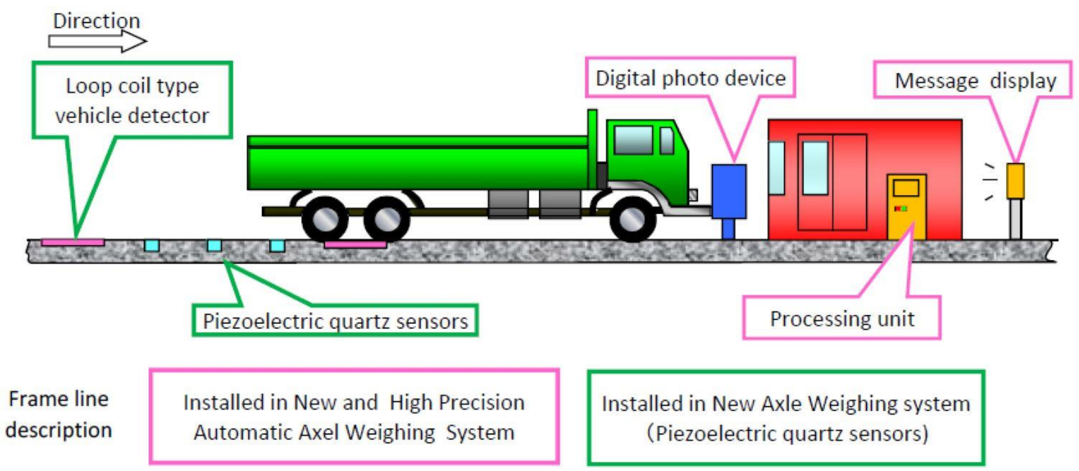


Figure 6 High-Precision Automatic Axle Weighing System and New Axle Weighing system with piezoelectric quartz sensors

New axle weighing systems is composed of 3 lined piezoelectric quartz sensors to weigh axle load. One Piezoelectric quartz sensor is 1m length and four sensors are connected in the line. Piezoelectric quartz sensors are using piezoelectric effect. Piezoelectricity is in response to applied stress and yields electric charge which is proportional to the force.The quartz element is rigid and stable to temperature.

The new axle weighing system uses same type of a photo device and a warning message display as the High-Precision Automatic Axle Weighing System. When the sensors detect overloading, the processing unit outputs signal to both devices in active mode.

Photo 2 Piezoelectric quartz sensors installation

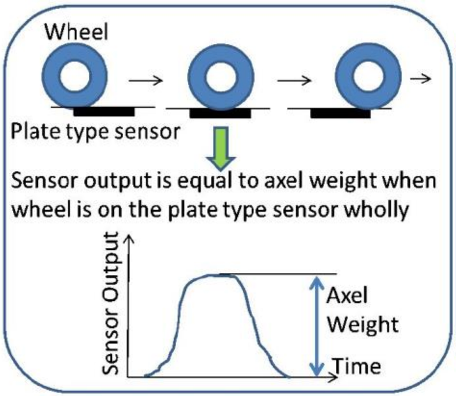
5. Differences between the plate type sensor and the piezoelectric quartz sensor

5.1 Measuring principle

See Figure 7, the plate type sensor capturing data and axle load of a vehicle are same. It is because whole wheel rolled on the plate type sensor.

The piezoelectric quartz sensors are bar shape sensors and narrower than wheel tread width. The sensors scale dispersive loads in motion. See Figure 8.

Both systems collect accurate data emitting running vehicle vibrations through processing solution.



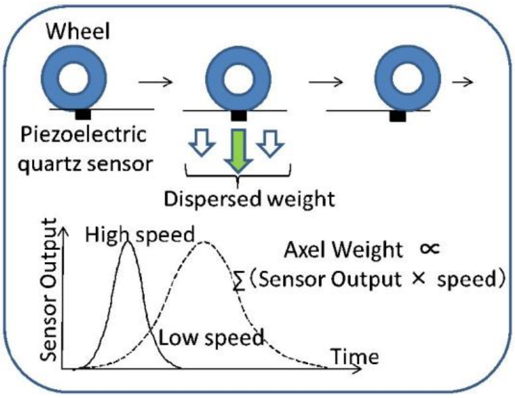


Figure 7 Plate type sensor **Figure 8 Piezoelectric quartz sensor**

The Piezoelectric quartz sensors detects axle load in dynamic mode, not in static mode. Passing speed through ETC gate is at about 30km/h in average. This speed will not cause errors of detection.

5.2 Installation

The plate type sensor and piezoelectric quartz sensors have to be placed in smooth and flat condition. Any causes of vibration on the sensors should be avoided to get accurate data. This means road surface conditions are an important issue for the sensor installation.

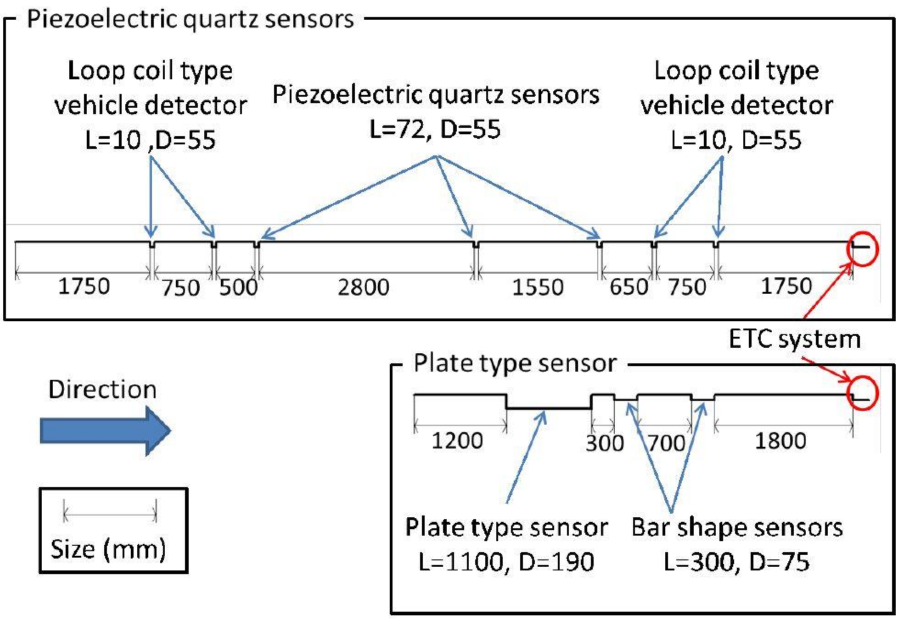


Figure 9 Cross-section views of Plate type sensor and Piezoelectric quartz sensors

The plate type sensor measures vehicle weight even wheels slip on the plate sensor, it is need to reconsider structural examination about the plate sensor weight (2.8t) and installation depth. Box-out method obtains a space of plate type sensor, water slot and conduit tube. The plate frame is fixed with anchor bolts. After plate equilibrium is confirmed, methacrylate resin grout Load cell and plate type sensor are placed in.

Figure 10 Construction technique

The piezoelectric quartz sensors are installed in a small slot in the road and fully embedded in the grout. Topcoat resin is flattered by grinder. The procedure can be easily installed than the plate type sensor. The grout is harder than road pavement, it keeps good durability.
The plate type installation takes about 1week per lane. The piezoelectric quartz sensors installation takes only one day per lane and minimizes to interrupt traffic.

5.3 Maintenance

For the plate type sensor weighing unit, maintenance procedures are by regular surveillance and cleaning and maintenance procedure in every piece with disassembling once in a year. After cleaning, its precision accuracy and installation flatness are examined using weights and test cars.
For piezoelectric quartz sensors surveillance is by visual inspection over its resin surface.
If there are cracks on the resin surface, the solution is to re-grout and polish the topcoat flat and smooth to pavement level. The procedures of piezoelectric quartz sensors minimize lane closure than plate type sensor unit.
The piezoelectric quartz sensors might be able to cut cost about 1mil yen per year. However, in case of defection, the sensors have to be replaced. It is still need to observe its failure rate.

6. New axle weighing system test

New axle weighing system test starts running at 2 lanes, Tsukamoto Toll gate in the expressway from January, 2015. At this toll gate had 4200 daily traffic volume and about 200 large vehicles in November, 2014.
At this site, the test examines functional system performance, installation availability and integrating efficiency with defining single automobile unit installed into other system.

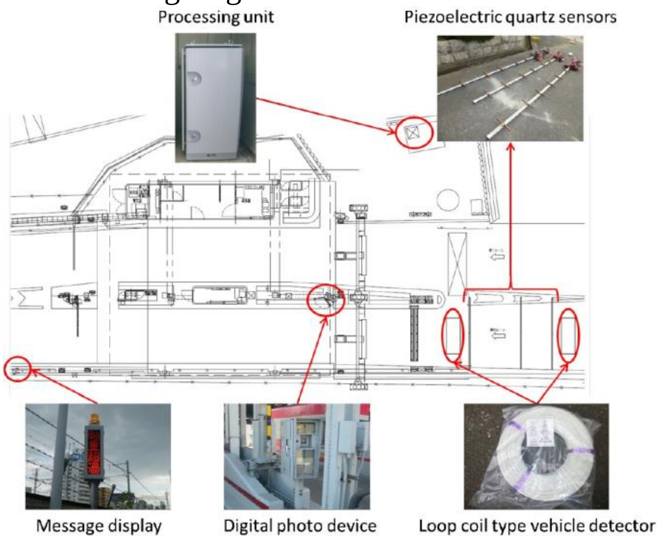


Figure 11 Layout at Tsukamoto Toll Gate

Running tests evaluated axle load weighing system accuracy. A two-axle vehicle ran for the test. The gross weight of vehicle was 15t and kept its load equivalency. The vehicle maintained each speeds of 5km/h, 10km/h and 15km/h. The test performed 75time at each speed. As the result of the test, the system accuracy was confirmed.

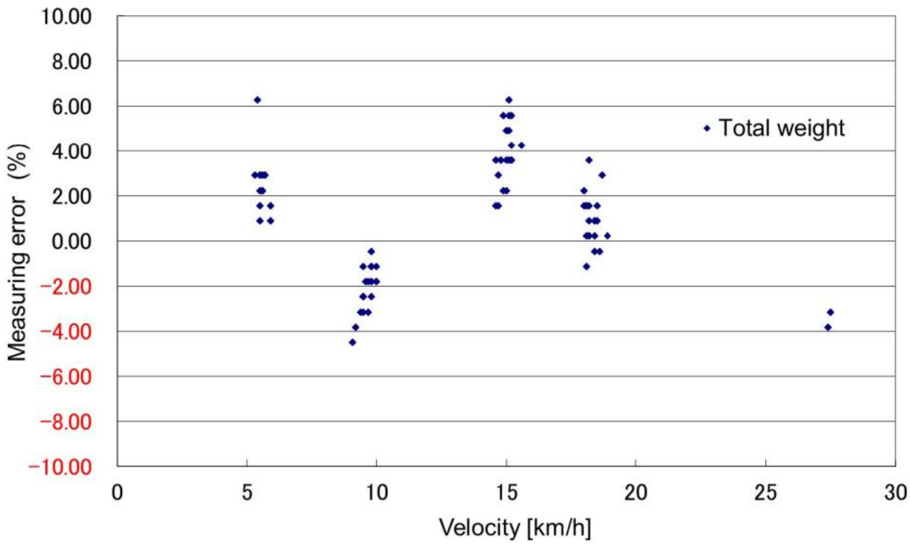


Figure 12 Running test result

High-Precision Automatic Axle Weighing System is regulated that inducing error is below 10%. As the result of running tests, piezoelectric quartz sensors of the new axle weighing system marked the error below 10%. This means the new axle weighing system is confirmed to work as well.

The next stage of evaluation of the system, lower emission level of axle load is input and multiple test truck run on the test course for integrating warning system efficiency. After the test, emission level of axle load will be set standard level, and the operational experiment will be planned.

7. Conclusion

The most effective control enforce is cooperation of crackdown act by police force and highway operation authority. However, this type of task plan is not easy to coordinate. It is highly expectation to use technical application for control of overloading on the highway.

We learned that the new axle weighing system should be expected lower cost performance from High-Precision Automatic Axle Weighing System and it should be reliable system to replace the overdue conventional system and deploy at more ETC gates. The new axle weighing system is useful for direct detect enforcement tool of overloading.

We will run extensive operational experiment of the new axle weighting system since then and keep developing weighing axle load system in the future.

IMPLEMENTATION AND ECONOMIC BENEFIT OF A WIM ENFORCEMENT SYSTEM

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Abstract:

This paper aims to show the key steps taken by Uruguay, a developing country, to implement an enforcement WIM system. The current system has been operating for more than 15 years. It has been certified by the National Legal Metrological Authority and accredited under the ISO/IEC 17025:2005 standard. This paper evaluates the economic benefit of the system from the standpoint of prevention of damage to road pavements.
The study of the economic benefit was conducted through the calculation of equivalent standard axle (ESA) under two scenarios: (a) with a WIM station (current situation), and (b) without a WIM Station, taking as a case study the Nuevo Berlin WIM station. The station is part of the National Roads WIM Enforcement System. The latter scenario developed from average historical overload in areas without enforcement, shows that the average overload is approximately fifteen percent. The results shows that after considering all the required investments (extra concrete and implementation of a WIM station), as well as and the operation and maintenance costs, there is a positive net present value (NPV) of USD 4.6 million.

Key Words: Weight Enforcement, Equivalent Standard Axle, Pavement Damage, Economic Benefit

Resumen:

Este trabajo tiene como objetivo mostrar los pasos clave adoptados por Uruguay para implementar un sistema de fiscalización de peso basado en tecnología WIM el cual ha estado funcionando durante más de 15 años y ha sido certificado por la Dirección Nacional de Metrología Legal y acreditado bajo la norma ISO / IEC 17025: 2005, así como el beneficio económico del sistema desde el punto de vista de la prevención de daños a los pavimentos de carreteras.

El estudio del beneficio económico se llevó a cabo a través del cálculo de los ejes equivalente (ESA) en dos escenarios: (a) con control de peso (situación actual), y (b) sin control de peso, tomando como caso de estudio la situación de la Estación de Nuevo Berlín. El escenario sin control, fue desarrollado a partir de sobrecarga media histórica en áreas de Uruguay donde no hay control de peso y que muestra que la misma es de aproximadamente 15%. El resultado del estudio muestra que considerando todas las inversiones necesarias (hormigón adicional vs ejecución de una estación de control), así

como los costos de operación y mantenimiento de la estación, se obtiene un valor actual neto positivo (VPN) de USD 4,6 millones .

Palabras claves: Fiscalización de Peso en Carreteras, Ejes Equivalentes, Daño al Pavimento, Beneficio Económico

1. Introduction

Uruguay is a country in the southeastern region of South America bordered by Argentina to its west and Brazil to its north and east, with the Río de la Plata to the south and the Atlantic Ocean to the southeast. It has an area of approximately 176,000 square kilometres. It is characterized by its strong political and social stability, based on its legal certainty and strong democracy. The political system has three main parties, which have alternated in government while maintaining a strong respect for the rules and the essential foundations of economic activity. From a transport point of view, Uruguay is positioned as a regional logistics hub with a prominent location regarding the richest cities of Brazil and Argentina. Its free trade zones law, free port, and airport and customs warehouses provide an ideal environment for the installation of distribution centres for the supply of goods to these cities.

Within this context, in 1996, the Government, with financial support from the Inter-American Development Bank (IADB) support, initiated implementation of a Weight Enforcement System on roads with WIM technology, under the Ministry of Transport and Public Works (MTOP). The MTOP had an international public tender for the construction, supply, installation, commissioning, and operation and maintenance of a Weight Enforcement System with five WIM stations to be located in the metropolitan area of Montevideo.

The goals of the project were, on one hand, the reduction of overweight on national routes, thus contributing to the durability of road assets, and on the other hand, to increase the number of controlled trucks, with a strong presence of the enforcement authority on national roads, so as to reduce road accidents and informality in the freight transportation sector.
Since then, the initial network of WIM stations has been transformed into an integrated system that operates on a 24x7 basis, evaluating more than two million of trucks annually and reaching more than 90% of the freight fleet. The network has been geographically expanded, to include more than 20 WIM Stations where weight, documents (national registration certificate) and dimensions are checked. Weight is evaulated using weigh-in-motion. Dimension conformity is performed with LASER technology.

The success of the project was based on the transparency of the system, the implementation of state of the art technology and strict, alignment with the standards set by regulatory agencies.
During the process, there have been successful milestones for the project, which this study intends to highlight. These milestones were:

- Regulation of road transport, establishing a maximum authorized weight per axle and total gross weight for different types of vehicles.
- Creation of a calibration laboratory, which depends on the National Transport Authority, with its own vehicles and standard reference mass traceable to the national reference standard. This laboratory verifies the functionality of a WIM system and its compliance with the standards.
- Establishment of metrological standards for the enforcement of a WIM System. These standards are according to the COST 323, ASTM1318 and OIML R134 Standards.
- Strong involvement of the National Legal Metrological Authority in the metrological control of the performance of the WIM system.
- Accreditation of every WIM Station as a testing laboratory pursuant to the ISO / IEC 17025: 2005 Standard. This internationally recognized certification is a sound basis for demonstrating technical competence before Conformity Assessment Bodies.

- Accreditation of the calibration laboratory pursuant to the ISO / IEC 17025: 2005 Standard.

The sustainability of the system is based, on the one hand, on a technology that can work with different suppliers, and on the other hand, on a strong electronic-software platform that allows the integration of various manufacturers and keeps the WIM System continually updated. This creates a highly versatile and easily adaptable WIM Enforcement solution capable of meeting the goals of a changing reality.

The system greatly exceeded the initial goals of overweight reduction and combating a casual attitude towards truck regulation, achieving a real change in the behaviour of most of the transport companies after they saw the equity and transparency of the system. The transport companies were integrated into the process. They adapted to the system by using the different vehicle categories in a more efficient ways while simultaneously respecting their respective limits.

There are still many challenges ahead, and their approach requires new technological tools and a legal framework adapted to the new technologies. They include the following:

- Identification and sanctioning of those who ignore the system and are continuously seeking mechanisms to evade it.
- Collaboration with the WIM station for safety checks for a further reduction of road accidents.
- Transformation of the WIM Station in a site that, beyond the necessary checks, does not turn into a delay to the carrier.
- Remote inspection/operation for all the sites.
- Mandatory radio frequency identification (RFID) for all transport units.
- Control of transport of hazardous goods.
- Optimization of the system for the management of fines.
- Support for the implementation of the Transit Guide.

The following diagram shows the organization chart.

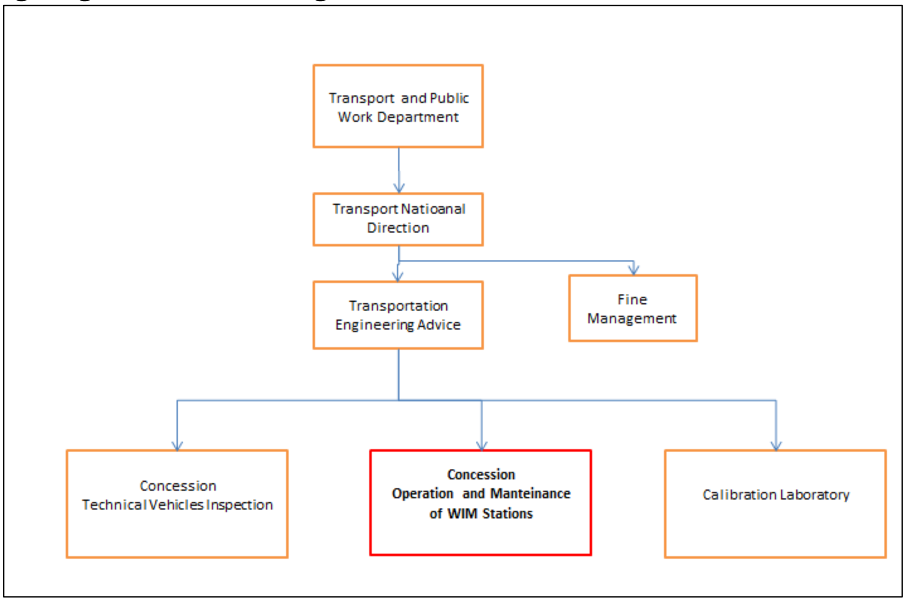

Figure 1 - Organization Chart

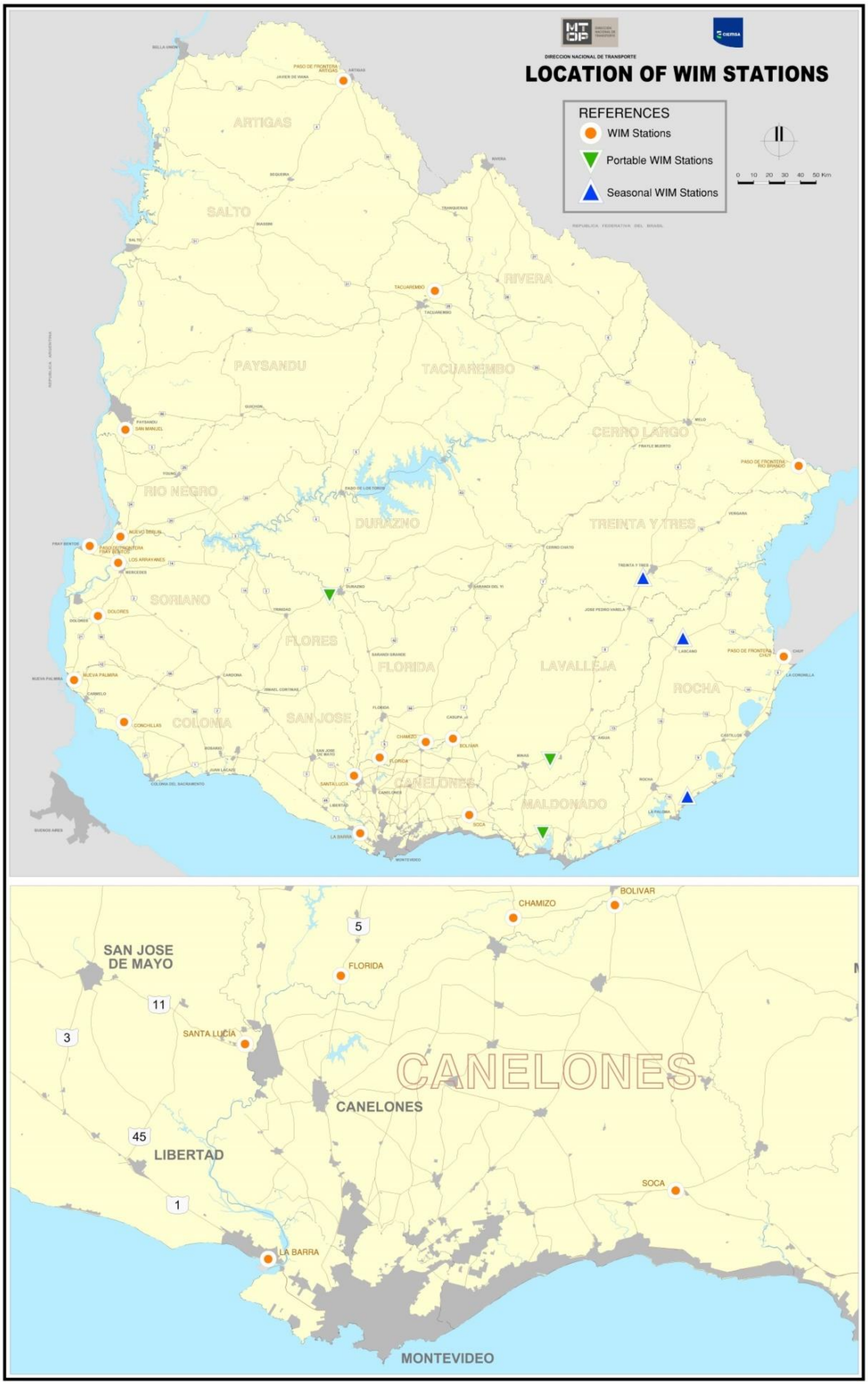

Figure 2 - WIM Station Network (red circles are WIM stations)

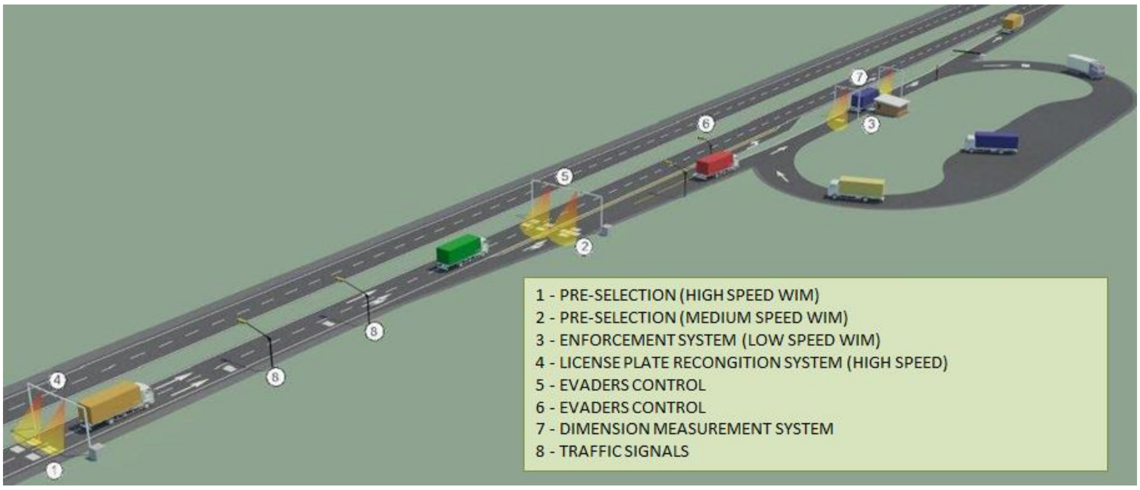

Figure 3 - Schematic overview of WIM station

2. Project Implementation

The project was based on four key elements:

- Versatility
- Strict alignment with regulatory agency standards
- Transparency
- Operations Management

Versatility

At the beginning of the system, a proven technology was chosen that met the initial performance requirements. However, the system had a great instability due to the claims of transport companies of errors and an unclear regulatory environment. These issues forced the implementation of multiple changes and several reviews of the software. In this context, the MTOP developed their own system, highly adaptable so as to facilitate the fulfillment of the objectives of the project.

The hardware and electronics were kept, but new software was developed. This was the key to the further development of the system. It allowed MTOP to make the necessary changes in a quicker and more efficient way.

After this first change, the electronic components were also changed so as to allow a system not dependent on any one vendor. This system is still working with different products of several vendors. This update allowed the implementation of a highly adaptable system that has been replicated in more than 20 WIM Stations.

Alignment with the standards set by regulatory agencies.

One of the key aspects of the whole development was having metrological performance standards validated by the National Legal Metrological Authority. This allowed the involvement of the CIESMA Transport Unit and the advancement to a further stage where the regulating body certifies the performance of the WIM station[1].

The COST323, ASTM E-1318 and OIML R-134 Standards were used as the basis for the development of the national standards. This development allowed the drafting of a law adapted to the country's circumstances and simultaneously aligned it with international standards. This was a fundamental step to provide transparency to the transport sector.

This achievement also meant the development of a calibration laboratory for metrological tracking of the WIM station network. The laboratory has its own pattern mass, vehicles, and static scale for reference weight for testing of WIM equipment. The static balance certifies the traceability according to the national regulations. The following figure drawing shows the control system structure.

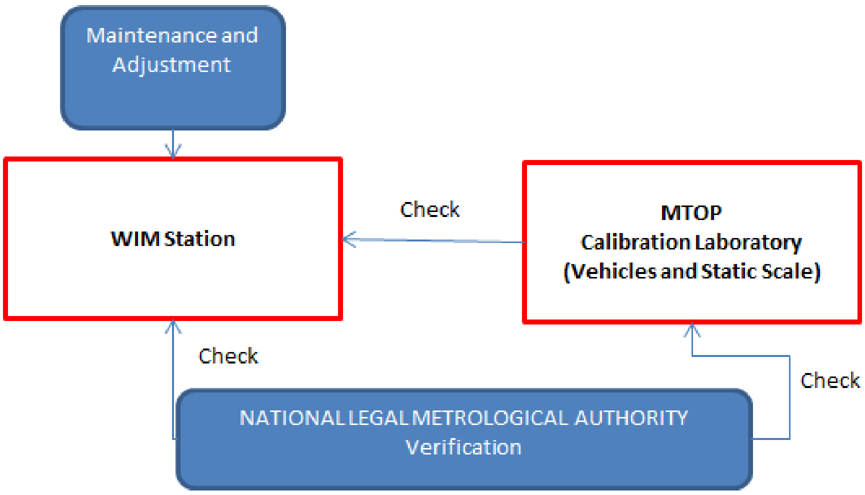

Figure 4 - Metrological Control Involved Parties

Note: The calibration process is performed by using at least three trucks with axle configuration T11S3, T11S2 and C11 loaded and unloaded. There are 60 repetitions for each truck at speeds between 3 and 7 km/h. The reference weights are obtained from a static scale which ensuring traceability to standard national mass.

Transparency

Transparency is obtained when third parties certify that the system complies with internationally recognized standards. To reach the transparency goal, both the WIM station and the calibration laboratory had their systems accredited under ISO/IEC 17025:2005 Standard.

Since 2008, the operation and maintenance of the system has been accredited ISO / IEC 17025:2005 Standard issued by the Uruguayan Accreditation Organization (OUA). This accreditation provides recognition from a third party of technical competence for the operation and maintenance of WIM station systems.

[1] Decree No 500/006 Technical Metrological Regulations.

The certification contributes to:

- Reliability: Ensuring the reliability of the results and the technical competence of the organization.
- Recognition: Certification is a nationally and internationally recognized status, eliminating the need of multiple audits.
- Feedback: The system is evaluated by experts skilled in the art, with experience in the examination of similar systems, and capable of providing valuable contributions to the improvement of the system.
- Assessment: Accreditation involves conducting internal audits and participation in proficiency testing that is in itself a valuable level of review and verification system.

Operations Management

The successful of the system is based on strict control and operations procedures, including

- Definition and tracking of operation parameters.
- Regular on-site checks of the station performance.
- Strictly enforcement of maintenance and calibration plans.
- Continuous evaluation of the operational personnel.

These best practices and implementation of cutting edge technology has helped ensure the success of the project.

Note: WIM stations operate 24hours a day, seven days a week. There are two people at the station at all times. One is the operator of the concession and the other is the public inspector. All the processes are automatic. Briefly, when a vehicle approaches to the control station, it´s detected by loop located after the entrance. Then:

- Activation of loop triggers the dimension check system, the weight sensors and the automatic identification system.
- The operator enters the license plate number and type of vehicle.
- The software receives as input the information entered by the operator and the readings from the sensors. The corresponding calibration factors are applied and calculates the vehicle dimensions and weights are calculated.
- Simultaneously, software checks the maximum weight and dimensions in the database for the vehicle detected.
- The information collected is showed at the screen of the operator with an automatic indication of whether it complies or not with the maximum authorized weight and dimensions.
- If the vehicle meets all the requirements, the traffic signal enables the vehicle continue its course towards the exit route automatically.
- If the vehicle does not meet with any requirements, the traffic signal sends the vehicle automatically to the parking zone. An automatic fine is generated in the screen of the public inspector.
- Simultaneously the software sends the data collected (weight, size, type, registration, etc.) and the fine (when applicable) to a central server located in the Ministry for later audit.

3. Economic Benefit

The study of the economic benefit was conducted, taking as a case study the Nuevo Berlin WIM Station. This station is part of the national roads WIM enforcement system belonging to MTOP.

There are at least two ways to calculate the effects of overloading on road pavement:

- Calculate the additional investment needed to build roads that are strong enough to deal with overloaded vehicles.
- Calculate the effects of overloading on the maintenance and repairs needed to compensate for the additional damage from overloading on the existing road network.

In this paper, the effect was estimated by calculating the additional investment. Also, it was done the inverse calculation, how many years would pavement life be reduced in the scenario without WIM Station if there is no additional investment. This is shown in the Results section.

The study was performed by calculating the equivalent standard axle (ESA) in two scenarios: (a) with a WIM Station (current situation), and (b) without a WIM Station. The scenario without a WIM Station was simulated and developed from historical average overload data from areas without enforcement. These data show that the average overload is approximately fifteen percent.

The Nuevo Berlin WIM Station is located in the western part of the country. It evaluates approximately 140,000 vehicles per year, consisting mostly of agricultural and forestry cargo to the ports of Nueva Palmira and UPM (Pulp Mill). The strategic location of Nuevo Berlin protects over 200 km of primary and secondary roads that link to the main road near the control station.

Figure 5 - Road network under the influence of Nuevo Berlin WIM Station

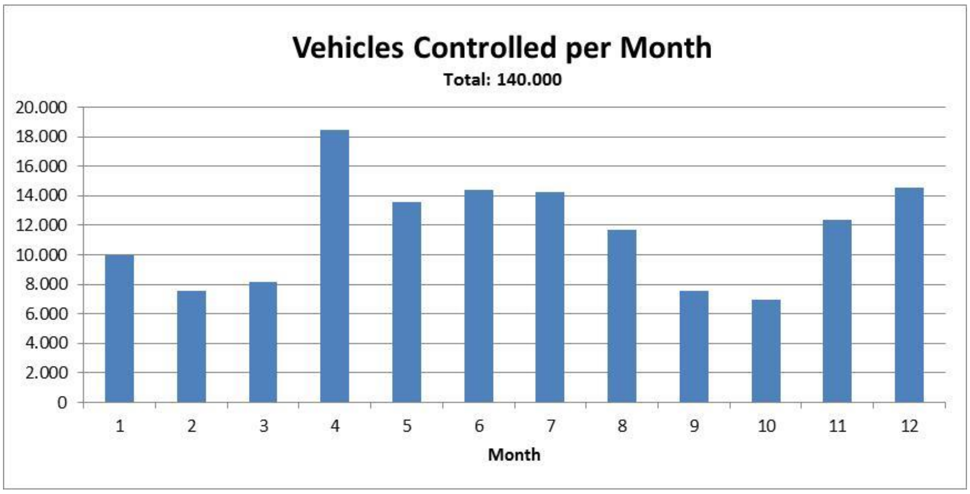

Figure 6 - Vehicles Checked per Month (2014)

In order to simplify calculations, the ESA consumption was calculated just for the five vehicle types most frequently weighed at the WIM Station: C12R11, T12S11, C11R12, T12S3 y T12S2S2. Together, they represent more than 80% of all vehicles checked at the station and are responsible for more than 95% of all the ESA measures in the station. Thus, the simplification is justified.

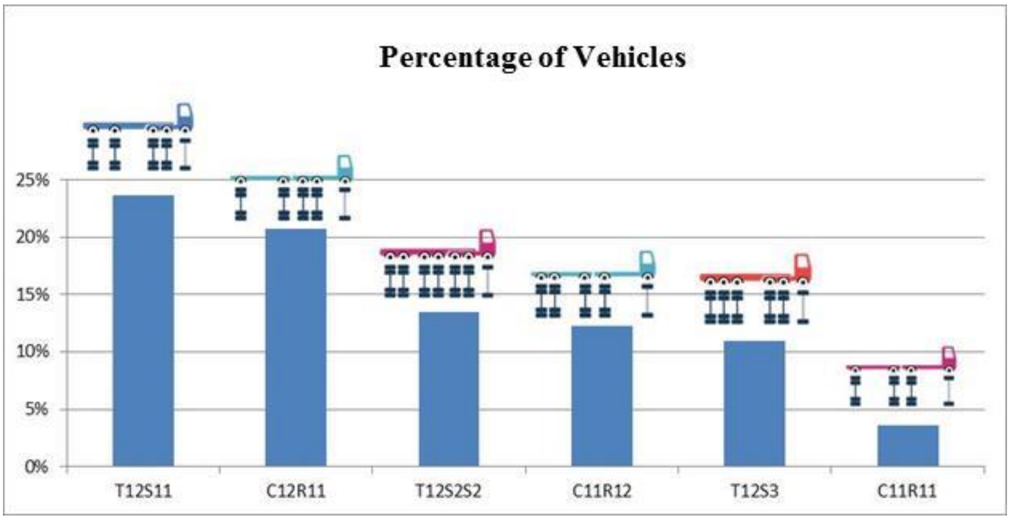

Figure 7 – Percentage of Vehicles

The ESA was calculated following the AASHTO recommendations for rigid pavements. The results of the WIM Station scenario are displayed in the following graphic.

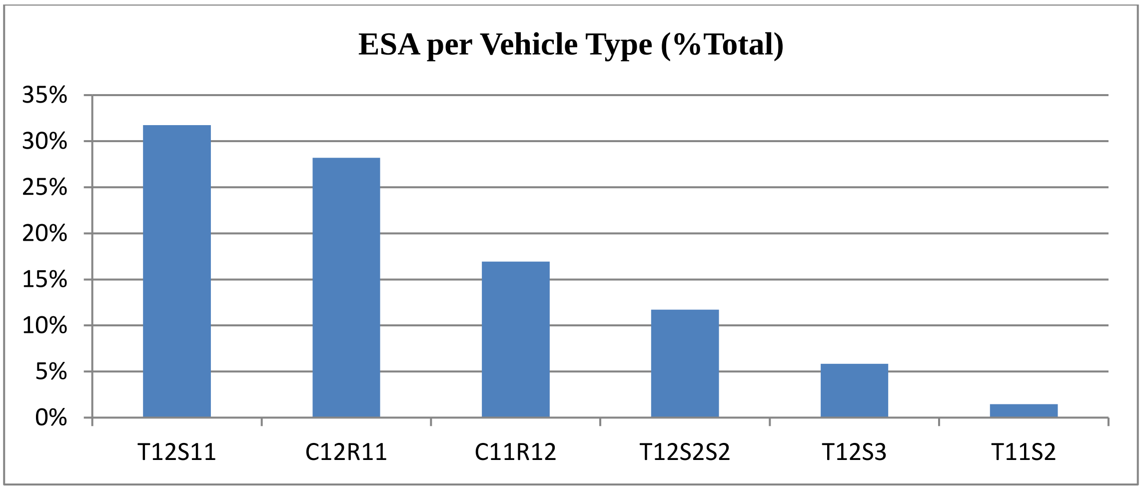

Figure 8 - ESA per Vehicle Type

ESA values in the scenario without WIM enforcement were calculated by applying the average historical excess, 15%[2], to the more frequent vehicles types, when the total gross weight exceeds 90% of the authorized maximum gross weight[3]. The assumption is that all the more frequent vehicle types which in the scenario with WIM Station weighed more than 90% of authorized maximum gross weight will be overloaded 15% without WIM Station.

The excess weight was only applied for single axles and axle-groups; it was not applied to front axles because these axles usually remain stable. The following table shows the results obtained.

Table 1 - ESA calculated for both scenarios, with WIM Station and without WIM Station.

Type	ESA (with WIM)	ESA (without WIM)
T12S11	223.414	460.789
C12R11	198.420	424.742
C11R12	119.177	254.103
T12S2S2	82.458	121.781
T12S3	41.161	218.784
Others	39.074	39.074
Total	703.704	1.519.273

So, the ESA with a WIM station is 703.704 for each year. The ten year total will be more than 7 million ESAs when a WIM station exists. Similarly, in the scenario without a WIM station, the total ESAs would be more than 15 million over ten years.

Then, we calculated the pavement thickness for each scenario according to the AASHTO 1993 recommendation for rigid pavement design. This is the equation used to determine concrete thickness:

[2] The average historical excess was obtained from surveys done in zones without WIM Stations from 1999 until 2007.

[3] It was assumed that vehicles under 90% of maximum cannot carry more weight due to volumetric restrictions.

$$\log ESA = Zr * So + 7{,}35 * \log(D+1) - 0{,}06 + \frac{\log\left[\frac{po-pt}{4{,}5-1{,}5}\right]}{1+\left[\frac{1{,}624E7}{(D+1)^{8{,}46}}\right]} + (4{,}22 - 0{,}32pt) * \log\left[\frac{Sc*Cd*D^{0{,}75} - 1{,}132}{215{,}63*J*\left[D^{0{,}75} - \frac{18{,}42}{\left(\frac{Ec}{k}\right)^{0{,}25}}\right]}\right] \quad (1)$$

The parameters were the following:

Table 2 - Parameters for the calculating of concrete thickness (D).

z_R	-1,037	Reliability Factor 85%
S_o	0,34	Combined standard deviation
po	4,2	Initial Serviceability Index
pt	2,5	Final Serviceability Index
S'_c (psi)	640,1	PCC modulus of rupture
Cd	1,0	Drainage coefficient
J	3,2	Load transfer coefficient
E_c (psi)	5.000.000	PCC modulus of elasticity
k (kg/cm^3)	8,4	Modulus of subgrade reaction

With these parameters and the ESA, was calculated, by iteration, to obtain the design concrete thicknesses (D) for both scenarios.

The results show that, for a rigid pavement and in the no-WIM station scenario, it was necessary an extra two centimeters of concrete thickness to ensure acceptable pavement performance for ten years. Therefore without any weight control by either the concessionaire road or the government, an additional 30.000 m^3 of concrete would be required to ensure the desired level of performance for 200 km of roads. The following table shows the calculated concrete thickness for each scenario.

Table 3 - Concrete thickness for each scenario

Scenario	Concrete Thickness (cm)	Additional Concrete (m3)[4]
With WIM Station	24,4	0
Without WIM Station	26,5	30.240

4. Results

Concrete costs approximately 240 USD/m^3. In the scenario without a WIM Station, the concessionaire road would expect to spend an additional 7.2 million USD for concrete.
On the other hand, in the scenario with a WIM Station, the concessionaire should expect the investment in public works and WIM system equipment, as well as the operation and maintenance cost (O&M) cost for ten years. The initial investment is about 600.000 USD, including public works, weighing equipment, evasion control system, and a high fidelity

[4] Additional concrete was calculated as 200 km * 7,2 m * (26,5-24,4)*1000; where 7,2 m is the road width.

CCTV for the capture of the license plates of trucks. The O&M cost is about 25.000 USD/month and includes the WIM station operators, supervision and technical direction, maintenance workers, and all the spare parts to ensure high operational availability.The following table shows the resulting cash flow[5]:

Table 4 – Differential Cash Flow of the Project

000´ USD	Year 0	Year 1	Year 2	Year …	Year 9	Year 10
Saved concrete	7.258					
Investment	-600					
O&M		-300	-300	-300	-300	-300
Free flow	6.658	-300	-300	-300	-300	-300

This cash flow shows that the Net Present Value (NPV), with a 6% discount rate, is 4.6 million dollars.

Based on these calculations the investment in weight control for roads can be highly profitable. The profit will depend on the behavior of the truck drivers, the road network, the average annual daily traffic, the construction cost, and the O&M cost.

On the other hand, if there is no additional investment, this structural package would result in acceptable pavement conditions for only 4 years and 8 months against 10 year in the scenario with WIM Station.

Other scenarios were studied to see if economic benefits also remain positive for other areas where the average excess could be different. The project's economic benefit was evaluated in scenarios where the average overload was between 5% and 20%. After calculating the ESA calculated for each scenario, the structural package required to keep pavement performance for the road in acceptable condition for a 10-year period. The following table shows a similar result for several initial conditions. The NPV has been simulated for different average excess and road network conditions.

Table 5 – Net Present Value for different scenarios of excess and road network.

		Road Network (km)			
	NPV (000´s USD)	150	200	250	350
Excess	5%	-774	-152	470	1.714
	10%	1.014	2.232	3.451	5.887
	15%	2.803	4.617	6.431	10.060
	20%	4.591	7.002	9.412	14.233

Although this work has not been extended to flexible pavements, the results should be the same or better in the case of flexible pavements.

5. Conclusions

[5] It is a differential cash flow, the cost of repair the pavement in ten year does not appear because they are in both scenarios.

The aim of this paper has been to demonstrate, at a moment when several Latin-American countries are implementing different road projects through Public-Private Partnership (PPP) or direct concessions roads, the economic benefit of implementing a WIM enforcement system.

From a pavement damage viewpoint, the possibility of implementing a WIM Station is determined by multiple factors. Particularly, the road network is a key element to the decision. It is necessary to invest a great time searching for a place that complies both with the minimum conditions against vehicle evasion and with the requirements of item 5 of the COST323 specifications[6].

After that, the selection of a robust and adaptable technology will allow the future operator to save a great deal of money.

Once these issues have been solved and the WIM station is operating, the metrological issues are a key element of the project. The scale must be calibrated following international specifications (such as COST323 or ASTM E-1318), with several trucks, both half and fully loaded, while it is also strongly advisable to have an external static scale to provide traceability according to international standards.

Throughout the project, the owner will have to implement a clear and efficient communication policy about the goals of the WIM Station that must include truck associations, public authorities, and legal metrology.

In summary, the key elements for a successful WIM project must include:

- Implementation of a state of the art, suitable, and reliable technology for WIM weighing.
- Successful implementation of strict control and operation procedures, and their compliance.
- A National Regulatory Framework in total agreement and aligned with all the WIM processes.
- A communication and diffusion strategy for alignment of the relevant stakeholders (truck associations, operators, public authorities, others).

6. Challenges

The final goal consists in transforming WIM Stations into an integrated control station for control of weight, dimensions, truck documents, freight documents, and mechanical status of the trucks (e.g.: brakes, truck lights, brake lights, tire pressure), allowing no evaders. The remaining challenges for the next years are the following:

- Improve the system for identification and punishment of those users that are station evaders
- Implementation of a Remote Operation System for most of the sites.
- Mandatory RFID for all trucks.
- Implementation of a hazardous goods transport control system.
- Optimization of the Fines Management System.

[6] Criteria for the Choice WIM-Sites, COST 323 “Weigh in motion of Road Vehicles” Final Report. Version 3.0. August 1999

- Integration of technologies for the checking of the mechanical status of trucks.

7. References

- COST 323 “Weigh in motion of road vehicles” Final report Appendix 1 European WIM specification Version 3.0, August 1999
- ASTM “Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Methods” – Designation: E1318-02
- OIML R134-1, edition 2003 “Automatic instruments for weighing road vehicles in motion. Total vehicle weighing.”
- ISO/IEC 17025:2005 “General requirements for the competence of testing and calibration laboratories”
- Decreto No 500/006: “Reglamento técnico metrológico de Instrumentos para pesaje de vehículos de transporte por carretera en movimiento” http://www.impo.com.uy/bases/decretos-reglamento/500-2006
- OUA: Uruguayan Accreditation Organization, member of IACC (Interamerican Accreditation Cooperation).

8. Annex – Decree 500/006 Summary

The item 6.5 of the Decree 500/006 provides that WIM Enforcement System must comply:

Gross-Vehicle Weight:

$$Pref * (1 - 0{,}02) + \frac{t * s}{\sqrt{n}} \leq P \ \leq \ Pref * (1 + 0{,}02) - \frac{t * s}{\sqrt{n}} \qquad (2)$$

Pref: gross-vehicle weight measured at reference static scale
P: gross-vehicle weight measured at WIM Station
t: Student variable with n-1 degrees of freedom and 95% level confidence
s: standard deviation at WIM Station
n: number of measurements

Axle-Vehicle Weight:

$$Pref * (1 - 0{,}03) + \frac{t * s}{\sqrt{n}} \leq P \ \leq \ Pref * (1 + 0{,}03) - \frac{t * s}{\sqrt{n}} \qquad (3)$$

Pref: axle-vehicle weight measured at reference static scale
P: axle-vehicle weight measured at WIM Station
t: Student variable with n-1 degrees of freedom and 95% level confidence
s: standard deviation at WIM Station
n: number of measurements

WEIGH-IN-MOTION SYSTEM TO MONITORING OVERLOADING IN A BRAZILIAN HEAVY TRAFFIC HIGHWAY





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Abstract

The traffic of overloaded commercial vehicles is a critical problem in many countries as traffic loads has been identified as one of the major contributors to pavement distress. In this study, the data obtained through a WIM system installed in the Brazilian federal roadway BR-381 was used to assess the weight compliance of heavy good vehicles (HGVs) with the Brazilian regulation. The objectives are to identify the size and nature of the overload problem on BR-381. The results from this study have indicated a significant percentage of violation involving overloaded heavy good vehicles in the highway (7.8%). Additionally, the degree of overloading has proved to be higher than expected, since the majority of the overload axles exceeded more than 20% of the weight limits per axle.

Keywords: Overloaded vehicles, traffic, heavy vehicles, Weigh-in-Motion, WIM.

Resumo

O tráfego de veículos comerciais com excesso de carga é um problema crítico em muitos países, visto que a carga aplicada pelo tráfego é uma das maiores responsáveis pelos defeitos no pavimento. Neste estudo, os dados obtidos do sistema WIM instalado na rodovia BR-381 foram utilizados para avaliar a conformidade de veículos pesados com a regulamentação brasileira. O objetivo é caracterizar o problema de sobrecarga na rodovia em questão. Os resultados deste estudo indicam uma significativa porcentagem de infrações de excesso de carga dos veículos comerciais que trafegam na BR-381 (7,8%). Adicionalmente, o excesso de carga se mostrou maior que o esperado, visto que a grande maioria dos eixos analisados apresentaram excessos superiores a 20% do limite por eixo.

Palavras-chave: Veículos com sobrecarga, tráfego, veículos pesados, pesagem em movimento, WIM.

1. Introduction

Traffic is one of the most significant factors influencing the pavement performance. It is mainly characterized by the loading configuration, magnitude and number of load repetitions of heavy vehicle traffic. In Brazil, the pavement damage caused by any vehicle axle is relative to the damage caused by a standard axle load. Therefore, the pavement is designed to resist a certain number of the standard axle load repetitions (N).

In Brazil, four major factors are considered to calculate the number N: (i) traffic composition; (ii) axle type; (iii) axle load; and (iv) frequency and number of load applications during the design period. Unfortunately, in most Brazilian highways there is no traffic load data collection, resulting in the unavailability of statistical data of this nature. Consequentially, it is common in pavement design to assume that vehicles are travelling with the maximum allowable weight established by Brazilian law (Balbo, 2007). However, the lack of knowledge of occurrence and extent of vehicle overloading can induce to incorrect estimations of the total number of standard axle load repetitions that is used in the pavement design and analysis. Additionally, the Pavement Design Guide published by the Department of Highways of the State of Sao Paulo (DER/SP) does not indicate what to consider regarding overloaded vehicles, which may lead to imprecise approximations.

As a consequence, the imprecise estimation of traffic may result in early maintenance and rehabilitation operations, increasing vehicle operation costs. The AASHO Road Test established the relationship between traffic axle load and pavement damage as an exponential geometric fourth power relationship. Pinto and Preussler (2002) also verified that the variation of axle overload and the corresponding pavement damage occurs exponentially. Similarly, a study by Kishore and Klashinsky (2000) found that 10% increase in the vehicle weight can accelerate pavement damage by over 40%. However, more important than the power, which can vary from 3 to 6 for flexible pavements, is that there is a significant increase in pavement deterioration when the axle load increases (Fernandes Jr., 1995).

In order to ensure pavement durability, regarding only the deterioration by overloaded vehicles traffic, weigh stations can be installed at strategic points at the road network to control the cargo transportation. This paper aims to evaluate the overloading of commercial vehicles at BR-381 highway through a Weigh-In-Motion (WIM) system installed in August/2015.

2. WIM Systems for Overloading Analysis

WIM systems have proven to be an attractive alternative for monitoring and weighting of heavy vehicles traffic, since it allows for the continuous collection of data about vehicle size, speed and weight. The use of WIM for this purpose eliminates the queuing at static weigh stations, resulting in considerable savings for both enforcement agencies and truckers. Furthermore, the data collected provides information of the real traffic composition, reducing approximations.

There are significant numbers of international studies on the use of Weigh-in-Motion technology to monitor the occurrence of overloading HGVs. Karim et al. (2013) states that WIM systems enhance the effectiveness and efficiency of the vehicle weight data acquisition. Furthermore, it was presented a significant percentage of violations involving overloaded commercial vehicles in Malaysia (21.5%). Chou (1996) suggests that the WIM equipment can be used efficiently to measure weight information, number and type of axles. Additionally, Chou's data analysis led to the conclusion that overloading condition in Taiwan is more severe than predicted, since the actual accumulative equivalent single axle load (ESAL) based on the WIM data collection proved to be 2.3 times larger than predicted, in addition to the already accounted 30% overload.

In Brazil, Brito et al. (2016) studied the commercial vehicle traffic through a Weigh-in-Motion system in the Brazilian roadway BR-290 to analyse the load spectrum. It was concluded that the WIM system provides the data of the actual traffic load on the highway. Regarding the overloading problem, it was found that, during the data collection period, 9.63% of the total number of vehicles monitored had some overload in at least one axle.

3. Case Study: BR-381

3.1 The Highway Characteristics

In this study, the data obtained through a Weigh-in-Motion system installed in the Brazilian federal roadway BR-381 was analysed. The highway is located in the Southeast of Brazil and connects the state of Sao Paulo and the Southern region of Minas Gerais. Thousands of heavy vehicles go through this highway daily, since Sao Paulo and Minas Gerais are two important economic regions in Brazil. In fact, heavy good vehicles have accounted for approximately 30% of all traffic in 2015, based on the traffic count data obtained from a toll near the WIM site installation.

3.2 The Weigh-in-Motion System

The Weigh-in-Motion equipment consists of inductive loops for detecting vehicle, sensitive piezoelectric sensors for the measurement of the stresses caused by the vehicles wheels, electric wires and cables. All these elements were inserted under the pavement and covered with grout for closing and electrical insulation, being interconnected with a system of data acquisition and monitoring cameras.

The WIM system was installed in August 2015. Since installation, the WIM has been calibrated twice by comparing a known test vehicle weights with the static weigh results. The accuracy of the WIM system is within +/- 10% of the static weight. Considering that, only those gross vehicle weight (GVW) data + 10% above the legal weight limits were considered overloaded. The data presented in this study is from September 2015 to January 2016 (5-month period).

The WIM data was filtered to remove questionable data and light-weight vehicles. Data was removed if recorded vehicle satisfied the following criteria: (i) gross vehicle weight less than 6.2 tons; (ii) individual axle weight less than 2.2 tons; (iii) tandem axles weight greater than 32 tons; (iv) axle spacing less than 3 ft (0.92 m); (v) total length greater than 118 ft (36 m) or less than 16.4 ft (5 m); (vi) total length greater than 50.5 ft (15.4 m) and GVW greater than 10.43 tons; (vii) GVW +/- 10% the sum of axle weights; (viii) speed greater than 105.6 mph (170 km/h); (ix) first axle weight greater than 10 tons; (x) GVW greater than 138 tons; (xi) sum of axles spacing greater than the total length; and (xii) individual axle weight greater than 18 tons.

The calibrated and validated WIM system was used for the purpose of identifying overloading for the nine most frequent categories of heavy vehicles in the traffic composition during the mentioned period.

3.3 The Compliance of Heavy Good Vehicles Weights with the Brazilian Regulation

Analysis and further selection of collected WIM data were carried out along nine categories of heavy vehicles. A total of 459,670 heavy vehicles data were analysed. Figure 1 presents the analysed categories and their respective legal gross weights. The legal gross weights presented do not consider the 5% (five percent) tolerance accepted by the Brazilian regulation.

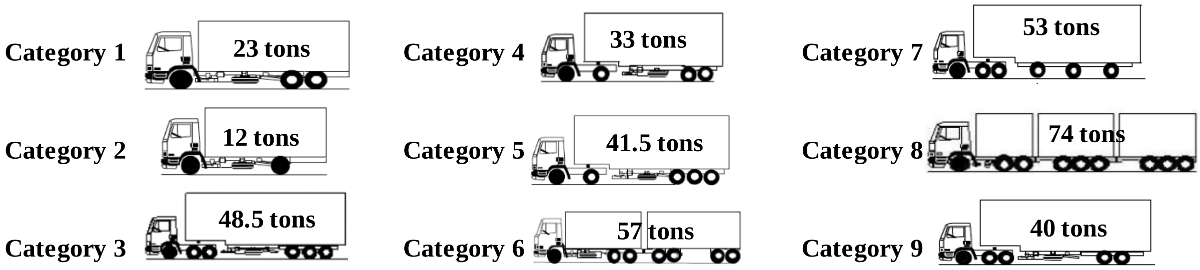

Figure 1–Legal gross weights of the heavy good vehicles in categories.

Figure 2 indicates the distribution of the analysed vehicles by categories. The HGVs from Category 1 are the most common in the BR-381. It can be noticed that the three most frequent HGVs categories account for more than 60% of the heavy vehicles analysed in this study.

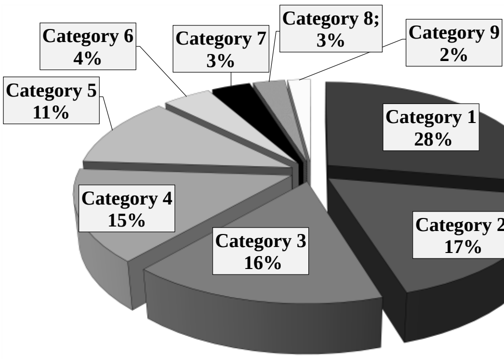

Figure 2 – Heavy good vehicles distribution per category.

The present legal limits in Brazil establish: (i) a maximum total gross weight depending on the vehicle class, and (ii) the maximum axle weight depending on its configuration (6, 10, 17 and 25.5 m-tons for single axles with single wheels, single axles with dual wheels, tandem axles and tridem axles, respectively). Since June 2014, the following tolerances are accepted by law to compensate for inaccuracies of scale readings: (i) 5% of total gross weight, gross combined weight, and maximum capacity traction limits; (ii) 7.5% of weight per axle limits for those vehicles that exceed the limits set out in the first item; and (iii) 10% of axle weights for those vehicles that do not exceed the limits set out in the first item (CONTRAN, 2014).

3.3.1 The Nature of the Overloaded Heavy Good Vehicles

In Brazil, the actual nature of the overloaded HGVs is unknown in most of the highways. Based on the WIM data analysis, Figure 3 shows the percentage of the vehicles analysed that exceed: (i) only the axle weight limits; or (ii) both total gross and axles weight limits.

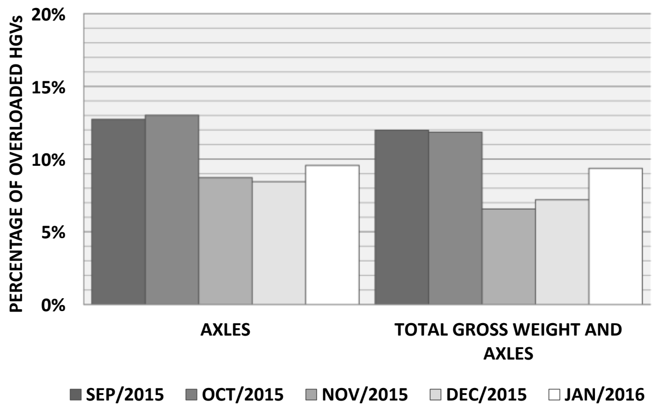

Figure 3 – Percentage of overloaded commercial vehicles.

Out of the 459,670 vehicles analysed according to Brazilian regulations, 35,822 vehicles were founded to be overloaded. One can observe in Figure 3 that from September 2015 to January 2016: (i) 52.5% of the overloaded HGVs exceeded both total gross and axle weight limits; (ii) 47.0% exceeded only the axle weight limits. The remaining 0.5% corresponds to the vehicles that exceeded their gross weight limit without exceeding an axle weight limit. This is an expected finding, as the gross weight limit is equal to the sum of the axle weight limit.

3.3.2 Overloaded Axles

Considering that of all the overloaded HGVs 99.5% had at least one axle overloaded, Figure 4 below presents the analysis of the overloaded axles. It shows that the single axles with single wheels presented the highest overloaded rates followed by the tandem axles. It is important to emphasize that overloaded axles with single wheels are predominantly the rear single axles, once the steering axle is hardly ever overloaded, which is consistent with Chou (1996) study.

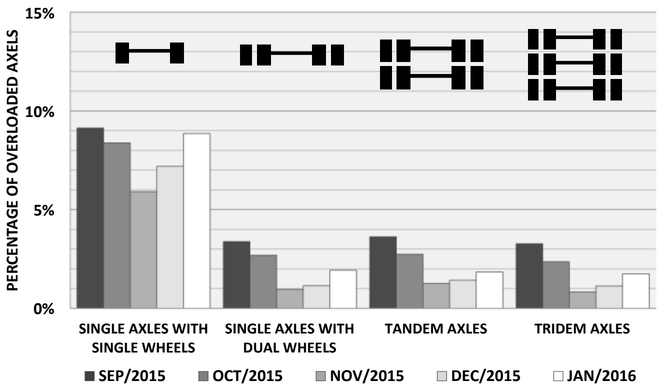

Figure 4 – Percentage of overloaded axles.

The axles overload distributions, considering the tolerance accepted by the Brazilian regulations, are presented in Figure 5. With the exception of the tridem axles, that represents mostly excesses ranging from 10.0% to 12.5% of the allowable limit in September/2015, analysis show that the majority of the overload axles exceeded more than 20% of the weight per axle limits. Although it is not the main topic of this paper, it is known that the effect of these overloads is a deterioration of the pavement structure at much higher rates than originally designed.

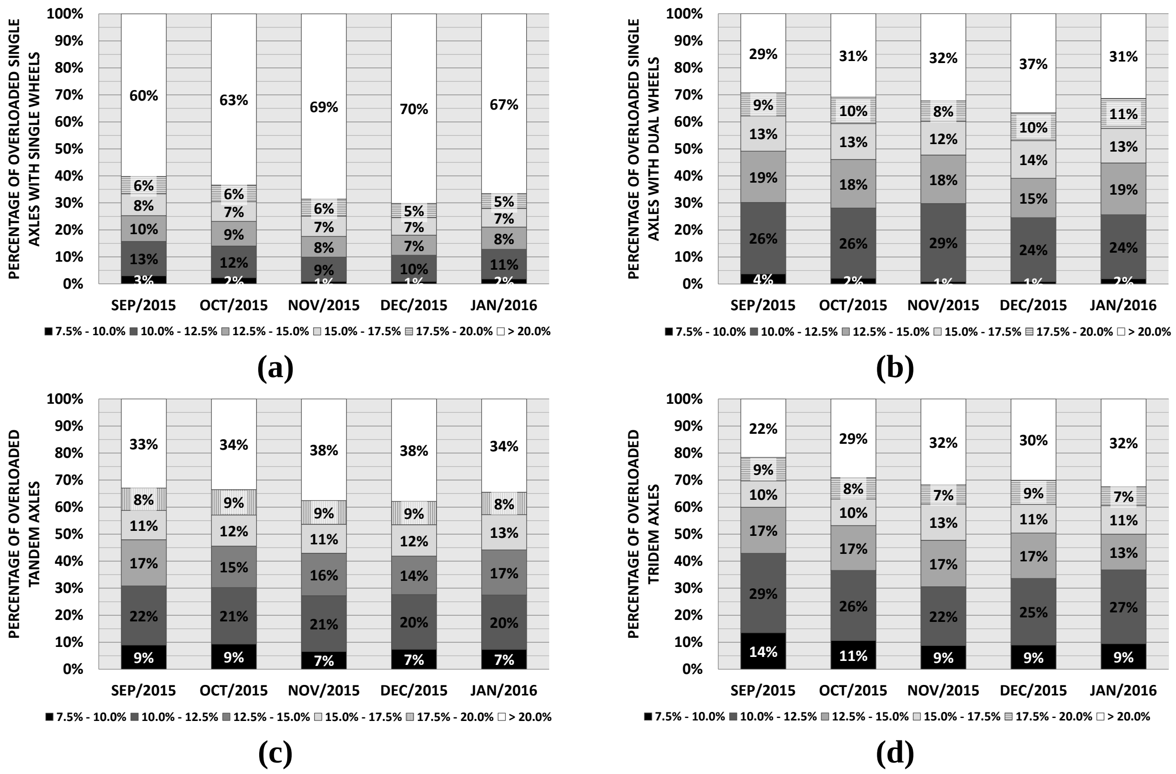

Figure 5 – Ranges of overloaded axles: (a) single axles with single wheel, (b) single axle with dual wheels, (c) tandem axles, and (d) tridem axles.

4. Conclusions

The objectives of identifying the size and nature of the overload problem on BR-381 were achieved. Significant percentage of violation involving overloaded heavy good vehicles is observed in BR-381. The overall analyses show that 7.8 percent of commercial vehicles are overloaded. The degree of overloading proved to be higher than expected, particularly for the rear single axles.

Weigh-in-Motion systems clearly have the potential to improve monitoring and weighting of heavy vehicles traffic in Brazil. Despite its high initial cost of installation, costs can be recovered by using more accurate traffic data on pavement designs. Moreover, WIM data can be used to determine the evolution of pavement condition over time. However, the successful implementation of WIM systems would require proper governmental effort and appropriate knowledge to ensure accurate vehicle weight data.

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APPLICATIONS OF WIM SYSTEMS
FOR ENFORCEMENT AND TOLL-BY-WEIGHT

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Abstract

A country's transport infrastructure is a public asset that actively supports its economy. Maintaining the network's quality and performance is therefore a critical issue for a nation. This primarily requires the effective control of the loads transported, which are the main source of the damage caused to roads, and also fair financing of infrastructure maintenance.

This paper aims to give an overview of the different ways in which weigh-in-motion stations are used throughout the world to enforce regulations on loads. In conclusion, it shows how weigh-in-motion stations can contribute to the implementation of a virtuous weight-based toll-charging system for heavy vehicles.

Key Words: Weigh-in-motion, WIM, overload, pre-selection, automatic issuing of penalties, toll by weight, road infrastructure, Ministry of Transport.

Résumé

Les infrastructures de transport sont un bien public qui soutient activement l'économie du pays. Le maintien de la qualité et de la performance du réseau est donc un enjeu primordial pour une nation. Il passe d'abord par le contrôle efficace des charges transportées, principale source des dommages occasionnés aux routes, et ensuite par un financement équitable de l'entretien des infrastructures.

Ce papier vise à donner un aperçu des différentes conditions d'utilisation à travers le monde des stations de pesage en marche pour faire respecter la réglementation sur les charges. À la fin, il montre comment les stations de pesage en marche peuvent contribuer à la mise en œuvre d'un système vertueux de péage au poids pour les véhicules lourds.

Mots-clés: Pesage en marche, WIM, surcharge, présélection, verbalisation automatique, péage au poids, infrastructure routière, ministère des transports.

1. Context

Road infrastructures are vectors of a country's social and economic development. First of all, they are the main channel for mobility and guarantee the fundamental right of every citizen to move around freely, including in the more remote and less populated areas. Secondly, they make a significant contribution to domestic terrestrial transport of goods: 74.9% within the European Union (Eurostat, 2016) and as much as 87.8% in France (INSEE, 2014).

Road infrastructures are also a national asset and as such have very high financial value which is often underestimated. In France, the cost of reconstruction as new of the network of publicly managed national roads and highways, which total approximately 20,000 kilometers, is estimated at €250 billion. If county roads and local roads are added (another million kilometers), the cost of this entire heritage is commonly agreed to be €2,000 billion (IDDRIM, 2014), almost the equivalent of the country's annual gross domestic product.

Allowing the intrinsic quality of this heritage to deteriorate would mean gradually reducing its value, as it will no longer be able to provide the services expected, and running the risk of it being impossible to repair if it became unusable. Maintaining the network's quality and performance is therefore a critical issue for a nation and for its economy. Weigh-In-Motion (or WIM) stations are core features of the new systems that can address this need.

2. Complying with loads regulations

The two main causes of ageing for road infrastructures are the effects of water, particularly as regards freeze-thaw cycling, and the loads supported (IDDRIM, 2014). The distress caused to the pavement by a Heavy Goods Vehicle (HGV) weighing 40 tonnes is equivalent to that caused by several thousand light vehicles, and that caused by an axle with a 15% overload is multiplied by a factor of 2 to 5 depending on whether the pavement structure is flexible or semi-rigid (NF-P 99-082, 1994). Damage related to the load supported is therefore mainly caused by HGV traffic, and especially by overloading.

While there is not much to be done about the weather, it is quite possible to monitor HGV traffic to ensure that it complies with the regulations in force concerning loads. We will give examples showing how WIM stations can contribute effectively to achieving this.

2.1 Control in France

2.1.1 Pre-selection of overloaded vehicles

France has used WIM stations since the beginning of the 1990s to acquire a better understanding of its HGV traffic movements. The first network of equipment was able to precisely quantify the percentage of HGVs in overload and the average overload, and to identify the most overloaded roads.

In order to develop a tool to combat overloading effectively, the Ministry of transport launched a programme in 2004 for the creation of a network of overload pre-selection stations covering the whole of France (Marchadour, Jacob, 2008).

This involved installing WIM stations right in the traffic flow, several kilometres upstream of the control areas where there was a certified static or dynamic weighbridge. Such equipment needs to weigh vehicles without slowing them down, determine their category and assess the potential overload per axle, per group of axles and per total weight, according to the regulations in force. When an infringement is presumed, the equipment provides in real time a ¾ photograph of the vehicle and an automatic reading of its licence plate to the enforcement authorities (police officers or controllers) located downstream at the control area, where they can intercept it. The stopped vehicles are then checked and fined if any infringement is found.

The contract was awarded to STERELA. The first stations were deployed in 2007 and today, the network includes 29 stations distributed throughout France. The weigh-in-motion equipment had to have at least Class C(15) accuracy, according to the COST 323 pre-standard (Jacob, O'Brien, Jehaes, 2002). Currently, all stations equipped with an array of intrusive sensors with one row of piezo-quartz sensors achieve Class B(10) accuracy (Debard, 2014). This accuracy is stable over time and valid for all types of traffic, which satisfies the reproducibility conditions R2 (III) according to COST 323.

Figure 1 – Example of a site in France

Regular use of this pre-selection network has had many positive benefits. Firstly, the statistics compiled round the clock by the WIM stations enabled the authorities to optimise inspection scheduling, by identifying the periods during which most offences are committed. Secondly, the pre-selection of vehicles in overload has increased the effectiveness of manual controls from an average of 25% to 96% (Dolcemascolo, Hornych, Jacob, Schmidt, Klein, 2015). This was followed by a significant decrease in risk behaviour and fraud, with the number of overload cases being halved in 5 years. It should be noted that to make these controls more punitive, the authorities changed the legislation in 2011. Fixed fines have thus been replaced by fines proportional to the excess weight in relation to the legal limits, which penalizes overloading more heavily.

Lastly, WIM stations do more than just weigh. They also measure vehicle speeds with very high accuracy. The maximum error is less than 0.4 kph (Dronneau, 2013). They therefore also detect any speeding offences depending on the category of the vehicle and can detect tachograph fraud as well. More generally, the centralisation of data collected continuously by WIM stations from all over France enables controllers to access the traffic history of the vehicles stopped. This information is valuable during controls because they can help detect fraud, by highlighting inconsistencies in driving time, rest time and transport dockets relative to the journeys made.

To make these operations secure, in 2014 the Ministry invested in automatic signalling systems (Dolcemascolo, Hornych, Jacob, Schmidt, Klein, 2015). This involves two variable message signs located respectively 600 m and 150 m upstream of the control area. The first panel informs drivers that control is mandatory and prohibits HGVs from overtaking. The second requires HGVs to leave the road and enter the control area. It is controlled by a device that dialogues with the WIM station located several kilometres upstream, and which automatically recognizes the pre-selected vehicles by reading their licence plates. Automating interceptions in this way frees up human resources that can be reallocated to their core mission, meaning that more vehicles can be inspected.

2.1.2 Direct enforcement

The ultimate aim of the Ministry of transport is to set up the direct enforcement of overloading, (*Contrôle Sanction Automatisé* – CSA). In this framework, since 2013 it has funded the "CSA overload" project, led by the IFSTTAR[1] and carried out with the assistance of the CEREMA[2], which aims to demonstrate the feasibility of direct enforcement of overloading with existing but adapted WIM technologies (Cottineau, Hornych, Jacob, Schmidt, Dronneau, Klein, 2015).

The principal challenge is to make the equipment compliant with the requirements of legal metrology, which means that 100% of the measurements must be accurate within the maximum permissible margin of error. To do this, WIM stations must eliminate from their measurements all values considered uncertain on the basis of validation criteria drawn from the analysis of the dynamic behaviour of vehicles. Given the low rate of overload of HGVs in France, the maximum permissible error is fixed at 5% of total weight, the objective being to achieve this performance for at least 30% of the vehicles in traffic.

Road tests are underway to assess the performance of the equipment provided by the different vendors of WIM systems associated with the project. They are conducted by the CEREMA, over several months, using rented reference vehicles and heavy vehicles from the traffic flow. Reference weights are performed in static way with axles scale approved 5E class according to the 5th project committee TC9SC2 (recommendation preceding the R134) of the International Organization of Legal Metrology (OIML). They are at least four times more accurate than those expected from WIM stations.

STERELA has created a multi-sensor array with four rows of piezo-quartz sensors. The calculated weight is equal to the average of the weight measured by each sensor line. The system was calibrated using the wheel weights of 2 semi-trailers from the test plan which each have performed 8 test runs. The following table compares the accuracies obtained with and without validation criteria for all vehicles of the test plan except those which were used for calibration.

The results show that the criteria for validating the measurements significantly improve the confidence level of the whole system and that only with these validation criteria the system is capable of meeting the requirements of legal metrology.

[1] *Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux* (French Institute of Science and Technology for Transport, Development and Networks)

[2] *Centre d'Études et d'expertise sur les Risques, l'Environnement, la Mobilité et l'Aménagement* (Centre for studies and expert appraisal of risks, the environment, mobility and development)

Table 1 – Accuracies obtained in France with the “CSA overload” project

Array of sensors	4 rows of piezo-quartz	
Measurements produced	All	Validated
Number of vehicles	127	81 (64%)
Mean error	-1.28%	-0.88%
Standard deviation	2.04%	1.47%
Reproducibility	R2 (II)	R2 (II)
Accuracy concerning total weight	A(5)	A(5)
Confidence interval	94.7%	99.4%
Maximal permissible error concerning total weight	5%	5%
Maximal error concerning total weight	15.40%	4.86%
Number of false positives	2	0

2.2 Control in Belgium

Belgium investigated WIM stations at the beginning of the 2000s (Cocu, Hoornaert, Delacharlerie, 2009). The Flemish Region installed its first WIM station in 2006, while the Walloon Region installed several stations between 2002 and 2005. The objective was of course to compile detailed statistics on the traffic, but especially to assess the possibilities offered by this technology for the control of loads.

On the strength of this first positive experience, the Public Service of Wallonia launched a call for tenders for five WIM stations for the pre-selection of vehicles in overload in 2014. The challenge was to respond to the request of the European Investment Bank which, in exchange for its agreement to finance the "Road Plan", wishes to ensure the longevity and the maintenance in good condition of the road infrastructures of the core network. In fact, the clearly-stated objective is to migrate rapidly to stations that issue penalties automatically. The equipment must therefore be capable of certification within the meaning of the Royal Decree relating to the approval, verification and installation of measuring instruments used to monitor the application of the law on policing road traffic (Albert, 2010), which sets the maximum permissible error at 10% of total weight. The main specifications required are as follows:

- Ensure that the minimum accuracy corresponds at least to Class B(10) under R2 (III) test conditions according to the COST 323 pre-standard,
- Detect cases of excess vehicle height,
- Detect the presence of heavy vehicles on prohibited lanes (hard shoulder and left-hand traffic lane).

The need to acquire approval at some point in the future imposes the choice of a single model system. It is therefore no longer possible to adapt the way sensors are installed to site conditions, as is generally the case with the cameras being mounted on bridges or on existing variable message signs. This is why the proposed solution incorporates a dedicated gantry. Similarly, the association between the detection of an offence and the taking of a photo of the vehicle's licence plate must be unquestionable. This is why infrared sensors for the detection of excess height are not installed on the gantry (which would have been the most practical solution), but on poles at the edge of the roadway, level with the array of intrusive sensors, which is where the cameras that read the licence plates automatically are focused.

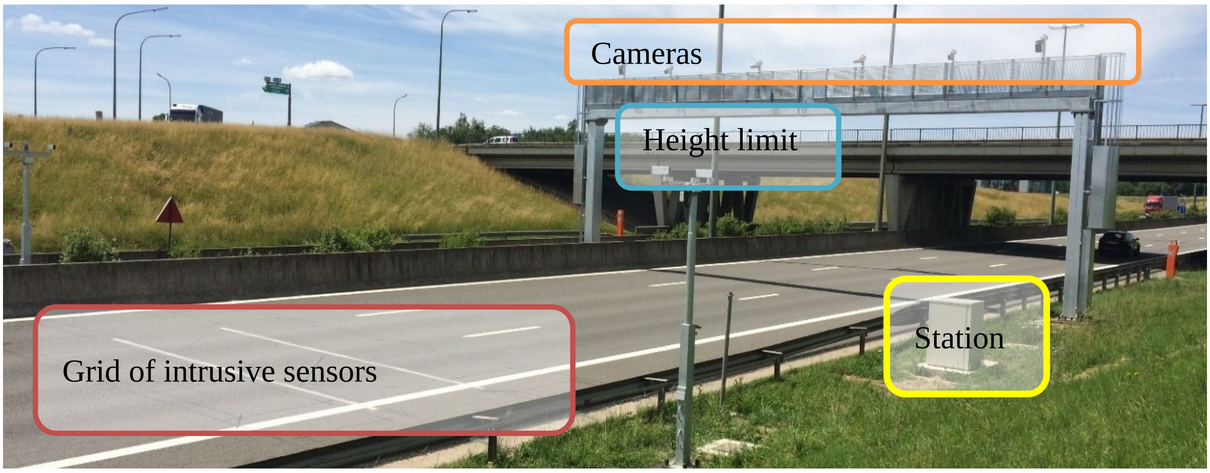

Figure 2 – Example of a site in Belgium

The tender was won by the "Tein Technology - Yvan Paque" consortium to which STERELA provided the five WIM stations, which were installed in 2015. The following table compares the accuracies obtained on initial acceptance of the first three sites. The tests were performed on 2 consecutive days with rented reference vehicles (rigid truck with 2 axles, rigid truck with 3 axles, tractor unit with 2 axles plus semi-trailer with 3 axles) and heavy vehicles from the traffic flow. Reference weights were performed at low speed (<8 km/h) using axles scale approved 1B class according to the international recommendation R134 (OIML).

Table 2 – Accuracy classes obtained in Belgium according to COST 323

Site	Saint-Ghislain		Louvain		Habay	
Lane	Right	Central	Right	Central	Right	Central
Number of vehicles	45	37	48	62	32	37
Conditions	R1 (I)	R1 (I)	R1 (I)	R1 (I)	R1 (I)	R1 (I)
Mean error concerning total weight	-1.22%	-1.79%	-2.35%	-1.59%	0.45%	-1.05%
Standard deviation concerning total weight	1.56%	1.19%	1.45%	1.86%	1.38%	1.68%
Total weight	A(5)	A(5)	B+(7)	B+(7)	A(5)	A(5)
Single-axle load	A(5)	A(5)	A(5)	A(5)	A(5)	A(5)
Load per group of axles	A(5)	A(5)	A(5)	A(5)	A(5)	A(5)
Load per axle in the group	A(5)	A(5)	A(5)	A(5)	A(5)	A(5)
Maximal permissible error (total weight)	10%	10%	10%	10%	10%	10%
Maximal error (total weight)	3.77%	4.81%	5.32%	6.69%	2.74%	-7.23%
Number of false positives	0	0	0	0	0	0

To obtain these results with only 2 rows of piezo-quartz without criteria of validation, it has been necessary to develop specific algorithms taking into account the lateral position of the vehicle's axles on the lane. The main challenge was then to calibrate precisely each sensor using a process which had to be time and cost effective. This was achieved by an innovative automatic self-calibration procedure. This kind of method was introduced in France in the early 1980's (Stanczyk, 1991) and improved in the 2010's (Klein, Stanczyk, Ieng, 2012). The system was thus calibrated after three month of use by setting automatically a correction curve so that the "same vehicles" were weighed in an identical manner regardless of their lateral position on the lane.

2.3 Control in West Africa and Equatorial Africa

The first WIM stations were installed in the francophone countries at the end of the 1990s, for statistical purposes. These installations revealed a very high level of overload of HGVs compared to the regulations. This situation is still observed today, as shown by the surveys conducted in December 2015 on a WIM station located on the A1 Motorway outside Dakar in Senegal. The proportion of overloaded HGVs is found to be nearly 40%, and, as these HGVs have a "mean aggressiveness coefficient" (MAC) about 30 times higher than non-overloaded trucks, they are responsible for 95% of the actual distress to pavements.

Table 3 – Analysis of Heavy Goods Vehicle traffic at Rusfique in Senegal

December 2015	Number of HGVs	% of HGV traffic	MAC[3]	% of aggressiveness of HGVs
"Legal" HGVs	15,644	61%	0.09	5%
Overloaded HGVs	10,047	39%	2.73	95%
Total	25,691	100%	1.12	100%

The immediate consequences are a significant reduction in the lifetime of the infrastructure compared to its design hypotheses. A recent report for the West African Development Bank (BOAD) notes that the mean lifetime of pavements in Mali is 4 to 6 years, instead of the 15 years initially planned (Adoléhoumé, 2015). The level of service offered by Africa's road network therefore seems unsatisfactory despite considerable investment. What is more, part of the funds currently devoted to roadway maintenance could be used for the country's economic development. Which is why Member States are strongly in favour of enforcing Regulation 14 of the West African Economic and Monetary Union (WAEMU) relating to the harmonisation of standards and procedures for controlling the gauge, the weight and axle loads of HGVs.

For this purpose, in the calls for tenders for the construction of new roads, the authorities now often include the requirement for a complete system for the monitoring, control and enforcement of overloading. Alongside these functional constraints there are also environmental considerations. As the stations are geographically isolated, they must be totally self-sufficient in energy and communicate over a wireless network. In addition, they must be able to store the data before sending, to take account of periods when the communication network may be unavailable.

Two systems of this type were provided and installed by STERELA in 2015, on the road from Ouesso to Sembe in the Congo. The proposed solution is built around a WIM station and a certified low-speed axle-weighing system, which both send their data to a central server. The

[3] The MAC is the mean aggressiveness of the vehicle with respect to the reference axle. The reference axle is set to 13t. The MAC is calculated by dividing the total aggressiveness of the specified traffic by the number of vehicles over the period. The aggressiveness of one vehicle is calculated according to the following formula (NF-P 99-082, 1994) :

$$Aggressiveness = \int_{i=0}^{i=number\ of\ axles} K \times \left(\frac{Axle\ load_i}{13}\right)^5 \quad where\ K = \begin{cases} 1\ for\ single\ axle \\ 0.75\ for\ tandem\ axle \\ 1.1\ for\ tridem\ axle \end{cases}$$

customer can thus remotely monitor all activity at the sites, with the percentage of HGVs in overload, the percentage controlled and the percentage for which fines are issued.

Figure 3 – Example of a high-speed WIM site in the Congo

Given the high rate of overload of HGVs, the degree of accuracy required for the WIM station is only 15% of total weight, which means that polymer or ceramic piezo-electric sensors can be used. The control area is equipped with a remote LED display to inform the driver of the weight readings. The operator has a tablet that automatically calculates the fine in the event of overload and a portable printer for publishing the weighing ticket. The whole setup is continuously powered by a solar farm.

Figure 4 – Example of a low-speed WIM site in the Congo

3. Financing roadway maintenance

3.1 Toll-by-weight

To finance roadway maintenance more fairly, the chosen system should make those who cause the greatest damage to roads pay the most. As damage to pavements is mainly caused by the loads they support, and more particularly by axle overloading, the fairest solution is to set tolls by weight that take into account the real distress generated by the vehicle on the pavement. The price for using roads would thus no longer be tied only to the category of the vehicle, but rather to the actual load of each axle, taking into account the axle configuration (single, tandem or tridem) and the wheel assembly (single, twinned).

Such a system may even become virtuous, if it encourages hauliers to use rigs that cause less distress to the pavement. There are many possible combinations (Schmidt, Glaeser, Hornych, Piau, Jacob, 2013). For an equivalent transported load, it will be to a haulier's benefit to use rigs subject to the cheapest category of tolls, and which consequently cause least damage to the pavement. More generally, the tariff structure for weight-based tolls must be designed to encourage hauliers to stop overloading their vehicles and to prefer rigs that comply with the regulations.

3.2 What WIM stations can contribute

There are two possible set-ups for introducing toll-by-weight. The first is to equip each toll lane with a weighing system. Although these can be highly accurate, low-speed scales are ill-adapted to dealing with significant traffic throughput and have high maintenance costs. More robust WIM stations are therefore preferable. However, it will be necessary to qualify their level of performance at low speeds. WIM stations are designed to measure the dynamic load of each axle. They are therefore particularly sensitive to transfers of load that occur when vehicles brake or accelerate.

The second choice involves installing WIM stations right in the traffic flow, several kilometres upstream of the toll posts, then re-identifying each vehicle in the toll lanes in order to match them with the axle loads measured upstream. Vehicles can be identified in several ways: automatic reading of the licence plate or reading of a specific badge using the Dedicated Short Range Communication (DSRC) standard. It is even possible to use a combination of these technologies to improve the quality of identification. The only precaution to take is to ensure that the vehicles are well positioned in their traffic lane at the time of weighing, for the measurement process to function correctly. Vehicles must therefore be prevented from changing lanes at the WIM station, by ground markings and appropriate vertical signals. And to avoid fraud, it is simply necessary to make vehicles that do not comply with these instructions pay an even higher fixed fine.

The second situation has several advantages. First of all, vehicles are weighed and identified in the traffic flow, without slowing down, therefore without loss of time and without any increase in CO_2 emissions. Furthermore, weighing at high speed minimises the dynamic effects which are detrimental to the accuracy of the measurements. In addition, a single WIM station is capable of managing the entire flow of traffic (whereas low-speed weighing systems must be installed in each toll lane), which reduces both investment and maintenance costs. Finally, weighing at high speed enables free-flow toll systems, which are incompatible with low-speed and static weighing systems.

4. Conclusion

Different countries employ different means to check for overloads. They depend on the proportion of overloaded HGVs, on the available human resources, the sites to be equipped, the short-, medium- or long-term objectives, etc. In all cases, weigh-in-motion stations make an effective contribution, either by the statistics they provide or by the pre-selection of offending vehicles. They are currently capable of achieving a good level of accuracy, and many of the projects are clearly intended to arrive at direct enforcement for overloading.

Beyond this purely punitive role, weigh-in-motion stations can facilitate the generalisation of new models of highway and motorway toll schedules that make road users pay in proportion to the wear and tear they generate, resulting in a fairer way of financing infrastructure upkeep.

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Session 7 : Direct Enforcement

Chair: Chris Koniditsiotis (TCA, Australia)

WIM Enforcement Systems – Five Years' in the Field Experience

   

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Abstract

The paper presents experience with precision and durability of WIM systems, side effects causing measurements errors, experience with weight violations and vehicle overload offense evaluation. Configurations using 2 and 3 rows of piezoelectric quartz sensors were type approved in 2010. Additionally, many other WIM systems were deployed in the Czech Republic over the past 5 years.

Keywords: WIM, direct enforcement, accuracy, durability, measurement errors, offense classification.

Résumé

Ce papier présente les retours sur expérience sur la précision et la durabilité des systèmes WIM, les effets secondaires qui sont responsables d'erreurs de mesure et les expériences avec l'évaluation des infractions des véhicules en surcharge.

Les configurations du système qui utilise 2 ou 3 rangs des senseurs piézoélectriques-quartz sont homologuées depuis 2010. En outre, beaucoup d'autres systèmes de pesage en marche ont été installés en République tchèque au cours de ces 5 dernières années.

Mots-clés: WIM, exécution directe, précision, durabilité, erreurs de mesurage, classification des infractions.

1. Precision and Durability (CAMEA, 2015)

In 2010, a WIM system was installed in Prague (Czech Republic) on a street leading toward the city center for type approval purposes. In order to achieve the highest possible accuracy, the road was repaired before the installation in a distance of approximately 75 m in front of and 25 m behind the sensors.

On this WIM site functional tests of weighing in motion in cooperation with the Czech Metrological Institute (CMI) were conducted for the purpose of type approval of the system for direct enforcement. The maximum permissible error of measurements as prescribed by CMI is 5 % for total weight and 11 % for each axle, group of axles and axle group. These parameters must be achieved with a 95% credibility (number of measurements, which are outside the tolerance limits must not exceed 5 %).

For the purposes of type approval 90 passing vehicles were measured according to the following schedule: three different types of vehicles (two-axle truck, two-axle truck with an axle trailer and a five-axle truck – semitrailer truck) were loaded with two different weights, each doing 5 passes for 3 speeds (25/50/75 km / h). One of the five passes was always conducted on the left and one on the right side of the sensors in the roadway.

1.1 The Accuracy of the Newly Installed System

For type approval purposes configurations using 2 and 3 rows of piezoelectric quartz sensors were type approved. The speed limit was 80 km/h and the spacing was 5 m for 2 rows and 1.9 m and 3.1 m for 3 rows. There was no road rutting, the longitudinal slope was 0.7 %, the cross slope was 2.8 %. If we evaluate the bias and the standard deviation σ (2σ to cover the 95% probability interval) achieved during testing, we get results plotted in the chart below.

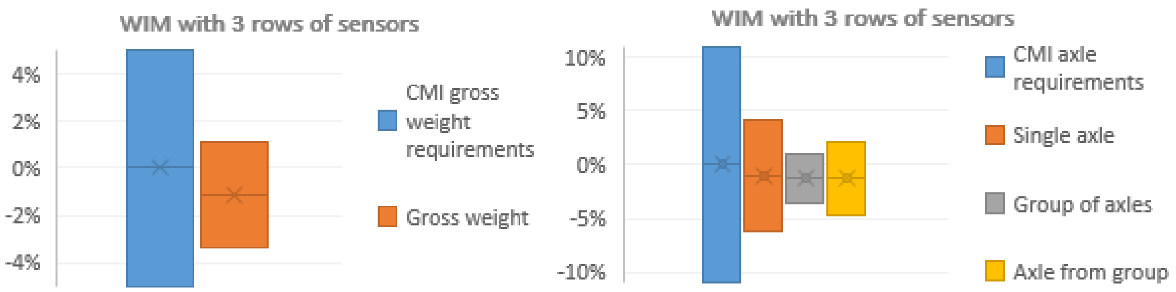

Figure 1 – Bias and standard deviation (2σ) results for WIM with 3 rows of sensors

Mean[1] -1.10 % when measuring the total weight is due to the fact that fewer vehicle passes with only one type of vehicle were used for calibration. The achieved standard deviation of the tests is 1.13 %, or 2.25 % for 2σ (plotted in the chart).

[1] *the value is an arithmetic average of measurement errors, which can be eliminated by changing the setting of the scaling factors.*

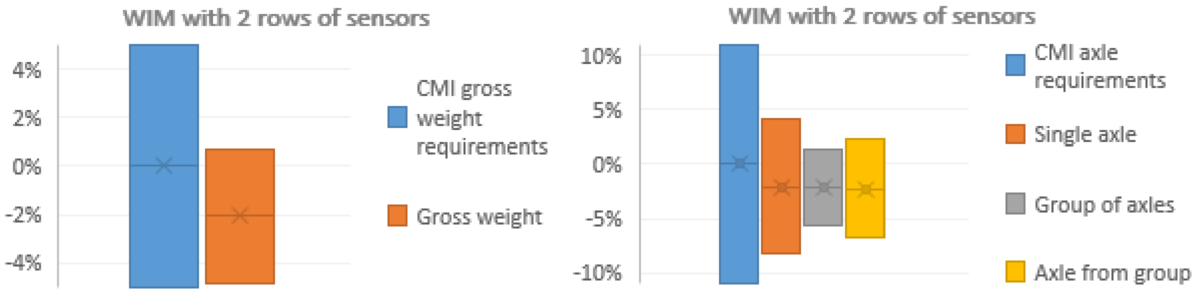

Figure 2 – Bias and standard deviation (2σ) results for WIM with 2 rows of sensors

Mean -2.08 % when measuring the total weight is due to the fact that fewer vehicle passes with only one type of vehicle were used for calibration. The achieved standard deviation of the tests is 1.40 %, or 2.79 % for 2σ (plotted in the chart).

The three-row system therefore shows an approximately 20 % lower standard deviation than the two-row system. The difference approximately corresponds with the expected result when comparing the standard deviation of an average of two and three repeated measurements of the same quantity.

When neglecting the mean, which can be easily compensated, the results clearly show that the WIM system was considerably more accurate during the tests than the requirements of CMI. The two-row and three-row configuration is applicable to the enforcement system. However, the three-row variant is preferable for many reasons as will be stated later.

1.2 The Accuracy of the System after 5 Years of Operation

A metrological verification of the WIM system was performed towards the end of 2015. The scheme of the verification was similar to the tests for type approval, with two differences:
• 60 vehicle passes were sufficient. Only 2 speeds were used, therefore there were less passes.
• The second vehicle was a three-axle vehicle without a trailer.

The technical condition of the road deteriorated significantly after five years of operation. Thanks to the hard CONFALT® (semi-flexible) surface there was no significant rutting, but there was a multiple transverse surface cracking. Likewise, the sensors have operated for more than 5 years and are most likely on the verge of their service life.

If we evaluate the offset (mean) and the standard deviation (2σ to cover the 95% probability interval conformity) achieved during the verification test, we get results plotted in the chart below.

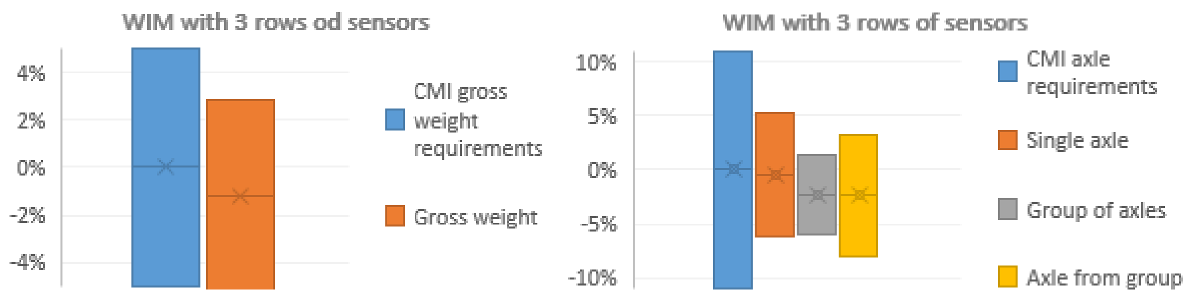

Figure 3 – Offset and standard deviation (2σ) results for WIM with 3 rows of sensors

Mean -1.25 % when measuring the total weight is again due to the fact that fewer vehicle passes with only one type of vehicle were used for calibration. The achieved standard deviation of the tests is 2.04 %, or 4.08 % for 2σ (plotted in the chart).

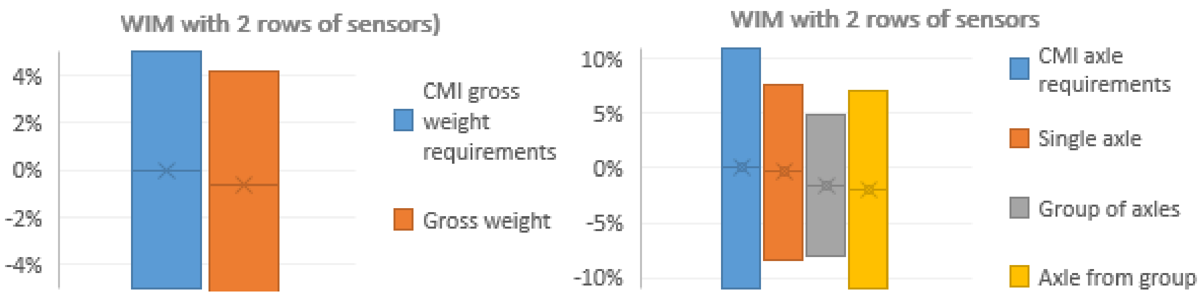

Figure 4 – Offset and standard deviation (2σ) results for WIM with 2 rows of sensors

Mean -0.62 % when measuring the total weight is again due to the fact that fewer vehicle passes with only one type of vehicle were used for calibration. The achieved standard deviation of the tests is 2.41%, or 4.83 % for 2σ (plotted in the chart).

1.3 System Service Life

The above results show that the accuracy of the weight measurement deteriorated approximately in half after five years of operation. The two-row system is practically metrologically unverifiable, since the results almost reach the requirement limits of CMI. On the other hand, the three-row system still exhibits characteristics inside the accuracy limit range, and it will probably be also verifiable in 2016. These results demonstrate a longer service life of the three-row system, which can be used for direct enforcement even after more than five years of operation. This service life expectancy difference would be even more profound if the system would be in a road surface of a lesser quality.

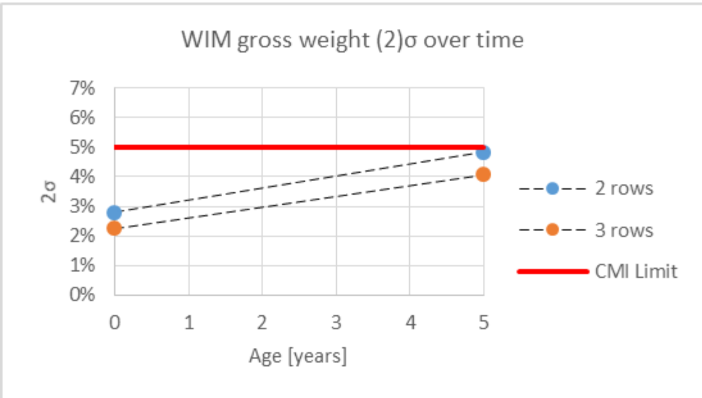

Figure 5 – WIM gross weight 2(σ) over time

An interpolation of the initial status of the two-row and three-row systems (for 2σ) and its deterioration after five years is shown in the previous chart.

The two-row system ceases to be (in ideal conditions) usable after the fifth year, whereas the three-row system is still usable and its service life can be assumed significantly longer than that of the two-row system while continuously reading from all installed sensors. This extended service life may seem negligible when taking into account the fact that the number of sensors also increases the cost of the sensors by 50 %. The price per unit of operational time of the sensors is approximately the same. However, it is important to realize that when recovering WIM stations, it is necessary to repair the road surface, organize traffic restrictions, install the sensors, carry out work design and many other tasks. In this case, the cost of the sensor array is an unimportant item in the total costs and the extension of the interval between necessary renovations of the WIM stations can lead to operational savings.

Three series of sensors are therefore preferable due to the longer service life of the WIM system, lower risk of complications during verification, higher credibility of the results and lower need of validation leading to higher system utilization.

It should also be repeated, that a suitable site, the quality of the road surface and its condition has an impact not only on the accuracy of weight measurements but also on the overall service life of the weighing sensors and the WIM system.

2. Side Effects Increasing the Measurement Error (CAMEA, 2015)

2.1 Roadway

All recommendations of various standards on the quality of the road, rutting, gradients and other factors are well known (see e.g. COST232). Their compliance is a prerequisite for the quality and high accuracy of the WIM system. However, it is necessary to point out the less visible characteristics of the road, which nevertheless have a significant influence on the quality of the measurements. These characteristics are related to deflection of the roadway and the homogeneity of the pavement structure.

2.2 Roadway deflection

One of the WIM systems installed in the Czech Republic displayed a phenomenon where during the hot summer months there had been a slight shift in the sensitivity of the system. This shift was most likely caused by an elevated roadway structure deflection after its warming up during the long days of heat. The chart below shows the dependency of the sensitivity of the WIM system and the average week temperature (all-week average). The shift in sensitivity ranged around approximately 1.5 % between summer and winter months. At the end of the summer, with decrease in temperature, the sensitivity returned to normal approximately corresponding to the initial calibration of the system.

The observed phenomenon demonstrates the need for caution during the selection of the road surface (road pavement), in which the WIM sensors are installed. The roadway must be sufficiently rigid in the whole range of weather conditions at the site. Newly repaired roads with a flat surface may also hide potential complications. The change in deflection need not be related only to temperature but can also other phenomena associated with the construction of the road or the ground can occur.

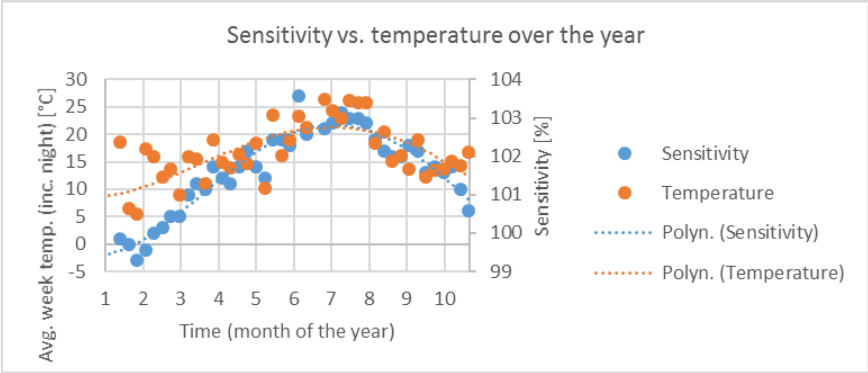

Figure 6 – Sensitivity vs. temperature over the year

2.3 Homogeneity of the Roadway Body

Another phenomenon associated with the homogeneity of the road body was found in a WIM system installed at a foreign customer. It was observed that vehicles moving on the right side of the lane were considerably lighter than those driving in the center or on the left. The error of the total weight was about 8 %. It was later discovered, that the road was originally narrower and was later extended to increase capacity. The right side sensors were positioned in the place of transition between the two segments of the road. The outer layer of the roadway pavement was new and homogeneous. The underlying layer of the former segment of the road and the extended segment probably did not exhibit the same physical properties leading to inaccurate readings of vehicle weight during sensor load in the transition.

Reduction in measurement accuracy due to inhomogeneity of the roadway body is very difficult to solve. Lower accuracy is nevertheless not the only impact associated with improper design of the road. Inhomogeneous roadways with poorly connected layers, transitions or other internal defects can have fatal consequences for both the installed sensors and the roadway itself.

2.4 Axle Group Weighing

During the many years of operation of WIM systems in the Czech Republic and abroad a lot of data was collected to be analyzed in order to monitor the accuracy and weigh measurement properties and other parameters. One of the major monitored characteristics of the behavior of a vehicle chassis was the behavior of groups of axles. Groups of axles and of two axles in particular show dynamic behavior that significantly reduces the measurement accuracy of axle weights in the group.

Normally when a weighing of vehicles takes place on a static scale (axle or wheel), the weights measured on groups of axles are similar to those of individual axles. The load rests on a whole group of axles and usually is distributed evenly among all the axles. The distribution deviation is in units of percent. This applies to most groups of axles, where the individual axles are of the same design.

During tests on dynamic scales, however, there is a change in weight distribution between the axles. This is caused by a combination of several factors, which are the torque of the axes, the construction and joints of the suspension, braking force, road surface interaction and suspension dynamics. Due to these factors, there is a dynamic change in the pressure of each axle group on the roadway. The axle weight measurements then do not match the static values and some axes may appear to have a bigger load. This fact is presented in the table using a sample of axle groups of several vehicles weighed by CMI and tests carried out in cooperation with the Transport Research Centre (CDV) (Doupal and Novotny, 2015).

Table 1 – Demonstration of different static and axle weight measurement results

	Static weighing					
	A1 [kg]	A2 [kg]	A3 [kg]	A1 [%]	A2 [%]	A3 [%]
2 axle trailer	4410	4417		-008	0.08	
2 axle trailer	6484	6557		-0.56	0.56	
3 axle truck (Group 2+3)	2900	2940		-0.68	0.68	
4 axle truck (Group 3+4)	9280	8860		2.32	-2.32	
3 axle truck (Group 2+3)	8380	8160		1.33	-1.33	
3 axles of semitrailer	5443	5640	5617	-2.22	1.31	0.91
3 axles of semitrailer	2540	2500	2460	1.60	0.00	-1.60
3 axles of semitrailer	6410	6460	6640	-1.44	-0.67	2.10
3 axles of semitrailer	7010	6930	6990	0.48	-0.67	0.19

The results of the tests showed that while the first axle of a group was slightly more loaded on a static scale, most cases resulted in the second axle being significantly heavier during dynamic weighing. The average weighing error of the first axle was -0.9 %, the error of the second axle was 4.5 %. In some cases, this load distribution was switched. The total group weight was practically always the same. Furthermore, if we focus on the standard deviations of the first and the second axle we find out that the sum of these numbers should be around 2.4 %. However, the weight of the group shows a standard deviation of 1.6 %. This difference is due to the fact that errors of the axles are random dependent quantities. If one of the axles is lighter, the other axle must be loaded respectively (an exception is the vibration of the whole mass of the vehicle above the group of axles). Due to these factors, the weight of the whole group is stable whereas the individual axle weights are relatively unstable.

Table 2 – Comparison of the expected and measured standard deviation

WIM	Static scale	8326	8108					
	Test	A2 [kg]	A3[kg]	Group 23 Err [%]	A2 Err [%]	A3 Err [%]	Balance	
LV-CH-W3	1	8177	8398	0.9	-1.8	3.6	-	+
	2	8175	8614	2.2	-1.8	6.2	-	+
	3	8498	8737	4.9	2.1	7.8	-	+
	4	8293	8555	2.5	-0.4	5.5	-	+
	5	7968	8567	0.6	-4.3	5.7	-	+
	6	8065	8476	0.7	-3.1	4.5	-	+
	7	8748	8009	2.0	5.1	-1.2	+	-
	8	8042	9003	3.7	-3.4	11.0	-	+
	9	8545	7956	0.4	2.6	-1.9	+	-
	10	7967	8385	-0.5	-4.3	3.4	-	+
	Mean [kg]	8248	8470	1.7	-0.9	4.5		
	σ [kg]	254	297					
	Measured σ	**3.1**	**3.7**	**1.6**	**3.1**	**3.7**		
	Expected σ			**2.4**				

In practice, one of the WIM systems installed on a road surface of lower quality and intended for pre-selection, presented some measurements where the axle group exhibited a misbalance of more than ± 10%. Although this situation does not directly relate to enforcement WIM systems, where the quality of the roadway is high, this discovered fact could have a major negative impact on fining of individual overloaded axle in a group. It is therefore recommended to evaluate only overloaded groups of axles because individual axles can be affected by important dynamic errors.

3. Experience with WIM Station Operations (CAMEA, 2015)

3.1 Road and Motorway Directorate of the Czech Republic Station in Modřice u Brna

In cooperation with Kapsch a WIM system was installed in 2012 in Brno Modřice. The system has a two-row configuration. It is using the toll system infrastructure (gantry, power supply) and is used to survey the possibilities of adding the vehicle weighing function to a toll system. Thanks to a new road surface installation, the system also meets the accuracy requirements for certified weight measurement.

3.2 Types of Overloaded Vehicles

The system provides a long-term ongoing monitoring of overloaded vehicles and the composition of the overloaded vehicles. Some of the results are summarized in the tables below. The numbers of valid enforceable violations during 4Q 2015 was 2135.

Table 3 – Modřice station long-term monitoring of overloaded vehicles results

Vehicle type	Count	Ratio [%]
5 axle semitrailer truck (1+1+3 axles)	1263	59.2
2 axle truck	184	8.6
4 axle truck	166	7.8
3 axle truck	148	6.9
6 axle semitrailer truck	89	4.2
Truck + trailer (2+2)	83	3.9
Truck + trailer (3+2)	56	2.6
Truck + trailer (4+2)	48	2.3
Other	96	4.5

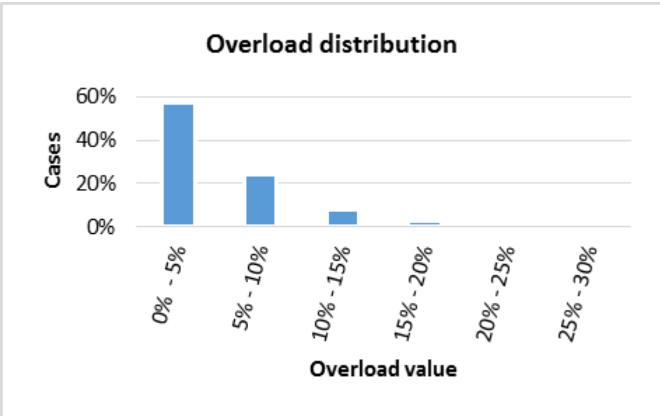

Figure 7 – Modřice overload distribution

The most overloaded vehicles are local carriers (54.1 %). The second most common, but significantly less represented (11.6 %) are foreign carriers on their way through the Czech Republic when crossing the Czech-Austrian border.

The most common overload is up to 15 % of the permitted maximum weight. The chart below shows the ratio of different degrees of overload. The chart does not distinguish the total mass, the weight of individual axles or groups of axles. The plotted values are the results of 5% tolerance deductions for total weight and 11% weight reductions for axles and axle groups. This tolerance deduction must be applied before the violation evaluation. The chart thus corresponds to the overload rate ready for enforcement. Long-term statistics show that the number of overloaded vehicles is approximately 1.7 % of the total number of vehicles over 3.5 tones.

3.3 Accuracy

Measurement accuracy of the WIM system has been repeatedly verified in cooperation with CDV and with the Police. Czech Police normally weighs vehicles at a rest stop approximately 4 km away from the WIM system. For vehicles that are not overloaded and can continue driving, it is then possible to compare the weight found on the axle scales with the weights measured later by the WIM system. Some of the values are shown in the table below.

Table 4 – Measurement accuracy

	WIM scale error						
Vehicle	A1 Err. [%]	A2 Err. [%]	A3 Err. [%]	A4 Err. [%]	A5 Err. [%]	A6 Err. [%]	GW Err. [%]
1	-1.2	4.2					2.2
2	-1.9	3.3		3.4			2.1
3	-5.7	7.5	0.4				1.1
4	0.9	1.0	7.0	-4.4	2.0	-2.1	0.9
5	-6.7	10.5	-4.5	-7.5	-4.6		-1.9
6	-1.8	-1.8					-1.8
7	-1.5	-6.6					-3.7
8	-6.9	-1.9	2.5	1.6	5.5		-0.2
9	5.3	-1.9					1.9
10	-5.7	6.1	-5.9	2.6	-7.7		-1.8
11	-5.2	2.0	9.0	6.0	-4.9		1.4
12	-1.6	-6.0					-3.8
	Mean						**-0.3**
	2σ (95)						**4.2**

3.4 WIM Station in Prague, Strakonická Street

Similarly, as in the previous example the composition of violations was evaluated at the Prague, Strakonická site which leads toward the center of the metropolis. Due to traffic restrictions, the occurrence of trucks is lower and their composition varies with. Nevertheless, 1333 valid offenses were recorded during 4Q 2015, i.e. 444 offenses per month.

Table 5 – Strakonická Street station long-term monitoring of overloaded vehicles results

Vehicle type	Count	Ratio [%]
5 axle semitrailer truck (1+1+3 axles)	389	29.2
3 axle truck	255	19.1
4 axle truck	248	18.6
2 axle truck	178	13.4
6 axle semitrailer truck (1+2+3 axles)	111	8.3
Truck + trailer (4+2)	59	4.4
Other	93	7.0

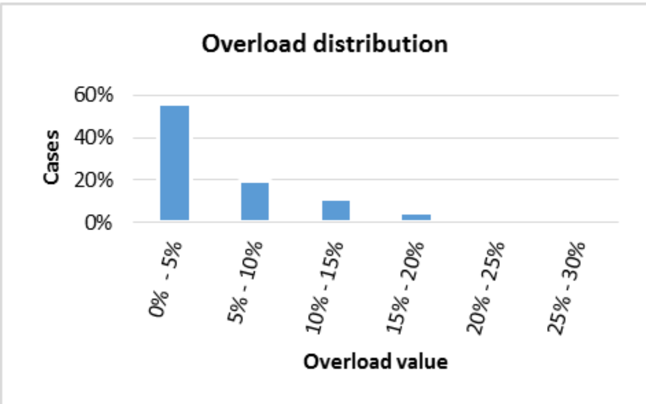

Figure 8 – Strakonická Street overload distribution

The most overloaded cases are local carriers. They form a full 90 % of all offenses, with practically no foreign carriers. The most frequent overloads again range up to 15 % of the permitted maximum weight.

4. Offense classification

In terms of the type of the offense, the driver can commit the violation of exceeding the gross vehicle weight (determined by the vehicle manufacturer) or the legally permitted weight. If the gross vehicle weight is higher than that permitted by the law, the operator must obey the legal limit. Equally, however, the operator must not exceed the gross vehicle weight, although it is in some cases lower than the legally permitted weight. The current Czech legislation does not allow the scale operator to inspect the vehicle register. Therefore, it is not possible to determine the gross vehicle weight for each vehicle. Operation of WIM systems is limited to checking the legal limits.

The legal limits in the Czech legislation (simplified) are linked to:
1. Construction of the vehicle (number of axles, type - tractor, trailer, trailer…, etc.).
2. Individual axle construction (single loose and driven).
3. Wheelbases in a group of axles.

Point 1 is solved in the WIM system by using accurate vehicle classification into more than 40 classes. With this classification, it is possible to determine the type of the vehicle and assign the proper weight limit with high precision. Thanks to the accurate classification it is also possible (in most cases) to solve point 2. For most conventional trucks with individual axles, only the second individual axle is driven.

Point 3 can be solved only in the case of precise measurement of wheelbases. It is very important to measure the wheelbases as accurately as possible for the WIM system to be able to determine the overload.

In one of the tests carried out in cooperation with CDV, the WIM system was tested for wheelbase measurement accuracy. In total there were 10 vehicle tests carried out at 3 different WIM sites in one day. The tests showed that all three WIM stations achieve the same results and the same wheelbase measurement accuracy which is significantly better than 1 %. In most cases (except for long wheelbases between a tractor and a trailer or a trailer with a mechanical backslash in the connection mechanism and other construction features) can achieve an absolute accuracy of ± 10 mm in 95 % of cases. (CAMEA, 2015)

A three-axle Mercedes Actros which was used as one of the vehicles during the tests can be used to illustrate the accuracy of the system. The wheelbase measurement error is deep below 0.5 % for 95 % of measurements.

Table 6 – Wheelbase measurement accuracy results

WIM	Test	329 cm	134 cm	WIM	329 cm	134 cm
	#	A12 Err [cm]	A23 Err [cm]		A12 Err [cm]	A23 Err [cm]
ST-CE-W1 (3 rows)	1	-1	0	LV-CH-W2 (2 rows)	-1	0
	2	-1	0		-1	0
	3	-2	0		-1	0
	4	-1	0		-1	0
	5	-2	0		-1	0
	6	-1	0		-1	0
	7	-1	0		-1	0
	8	-	-		-1	0
	9	-	-		-1	0
	10	-	-		-1	1

	A12 base	A23 base
Mean [mm]	-1	0
2σ (95 %)	**0.20 %**	**0.35 %**

The ability of the system to classify vehicles in a detailed way (and correctly) and measure the wheelbases precisely is essential for heavy vehicle enforcement, although it is not required by the legislation. In general, an autonomous enforcement system must be able to recognize as many vehicle parameters connected with the legally permitted weight limits as possible with the highest possible accuracy. The only way the system can reach an optimal state is when it detects the lowest possible number of false violations for investigation purposes while the lowest number of violators avoid their penalty. For this reason, the WIM system must integrate additional features such as twin tire detection, dimension measurement, front and rear ANPR cameras, measurement validation and more.

5. Conclusion

The previous chapters can be summarized in a few points:

- We recommend the use of 3 rows of weighing sensors. This configuration has the advantage of greater accuracy, longer service life (verifiability), higher reserves in accuracy in case of negative external influences and higher credibility of the results. CAMEA's WIM system measurement validation using this configuration is able to determine a higher number of weighings as valid and the WIM system has an increased efficiency. Two-row systems are associated with the risk of a shorter service life (verifiability) and complications during metrological verification.
- Considering the dynamic behavior of individual axles joined in a group of axles, leading to lower measurement accuracy of axle weights in a group, only axle group violations are recommended to be evaluated. We do not recommend the use of individual axle weights in a group of axles as a reason to penalize the carrier.
- 'As close to perfect as possible roadway pavement is the key to accurate weighing. Besides the usual parameters such as the road gradient, rutting and the technical condition of the road, we must also take into account the parameters of construction materials and the composition of the road and its subsoil. Some repairs or modifications of old roads that are not apparent at first glance may reduce the accuracy or durability of the WIM system.
- Measurement accuracy is not the only parameter that is important for the operation of an enforcement WIM system. The system's ability to correctly assign specific legal limits for

a particular vehicle, including additional documentation required by the law is crucial for the usability of an enforcement WIM system in practice.

- Although lawmakers are still unable to properly solve the problems of high-speed weighing, based on an independent legal analysis the WIM systems should be able to be operated in the full extent of their intended use to punish overloaded carriers.

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START OF DIRECT ENFORCEMENT IN THE CZECH REPUBLIC

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Abstract

The Czech Republic was the first country in the European region to start using HS WIM systems for direct enforcement concerning weighing road vehicles. The Transport Research Centre (TRC) designed the "METHODOLOGY for the design and operation of control systems for weighing vehicles in motion (WIM)", this document has been approved by Ministry of Transport in Czech Republic.
The paper presents the most important parts of additional field tests regarding to fulfill all of the metrological and technical requirements, as well as any practical experiences with the initial verification of WIM system in realized Czech Metrological Institute and TRC.

Keywords: WIM, Police, haulage, direct enforcement, research project.

Résumé

La République Tchèque fut le premier état européen à utiliser les systèmes de pesage en marche à haute vitesse pour la mesure directe du poids des véhicules. Le Ccntre de recherche pour les transports (TRC) a défini la méthodologie pour la conception et les opérations de contrôle des stations de pesage en marche, et celle-ci a été publiée. Elle a également été approuvé par le ministère des transports de la République tchèque.
Cette publication présente les points les plus importants concernant les tests supplémentaires à effectuer sur site pour respecter les conditions techniques et métrologiques, ainsi que le retour d'expérience des vérifications initiales de système de pesage en marche réalisées par l'institut de métrologie Tchèque et le TRC.

Mots clés : WIM, Police, contrôle sanction automatisé, projet de recherche.

1. Introduction

The Czech Republic was the first country in the European region to start using HS WIM system for direct enforcement of vehicle weight. Paper describes regulatory framework of the vehicle weight control in the Czech Republic and metrology requirements of the HS WIM enforcement. Lastly, paper offers a commentary on results and experiences with HS WIM.

1.1 Regulatory framework of vehicle weight enforcement in the Czech Republic

The legal basis for vehicle weight enforcement is stipulated by Sections 38a – 38d Act no. 13/1997 Coll., on the Road Network, as amended (hereinafter, "Road Network Act") and Chapter X of Decree no. 104/1997 Coll., Implementing the Act on the Road Network, as amended (hereinafter, "Road Network Decree").[1] Specific provisions on vehicle weight enforcement were enacted and came into force on 1 July 2000. Related issues of road traffic safety and technical conditions of vehicles in operation are governed by different laws, namely Act no. 361/2000 Coll., On Traffic on the Road Network and on Changing Certain Acts, as amended, and Act no. 56/2001 Coll., On the Conditions for the Operation of Vehicles on the Road Network, as amended, including their implementing decrees.

The Road Network Act recognizes two categories of vehicle weight control. Although the two categories are called low speed vehicle weight inspection (hereinafter, "LS WIM") and high speed vehicle weight inspection (hereinafter, "HS WIM"), use of static scales is not excluded. The reason is that the Road Network Act defines HS WIM as weight enforcement with non-transferable scales, which does not require that vehicle diverts from operation. On the other hand, the LS WIM is defined as weight enforcement with any other technical facility, which does require diversion of vehicle from operation. Therefore, measurement of vehicle weight with static scales falls into the latter category and is allowed.

Only vehicles of categories listed in Section 38a Road Network Act are subject to weight enforcement under the Road Network Act (i.e. vehicles of N_2, N_3, R3, R4 category and vehicle combinations consisting of a motor vehicle from N_2, N_3 category coupled to a trailer/semi-trailer of O_2, O_3, O_4 category. Vehicle weight enforcement only applies to motorways, roads and municipal roads.[2] As far as the methods and performance of weighing itself are concerned, the Road Network Act is rather succinct.

During the LS WIM vehicle is diverted from operation to site, which is maximum 16 km far away including return journey. Document containing weighing results is issued and handed over to the driver and later sent to the vehicle operator (haulier). During the HS WIM vehicle is not diverted from operation and thus the Road Network Act. Scales are built into the road infrastructure and the driver of the vehicle is obliged to submit the vehicle to a control, which is carried on the route of the vehicle regardless if the driver is familiar or not with the place where the HS WIM is performed.

The absence of more detailed rules on the LS WIM performance does not jeopardize the legality of entire procedure. It is however necessary to note that both the LS WIM and the HS WIM shall be carried out with scales that are legally controlled measuring instrument. The Act no. 505/1990 Coll.,

[1] Public database of legislation of the Czech Republic is available at site http://portal.gov.cz/ in Czech language.
[2] Highway is designed for long distance transport or international transport. 1st class *roads* are designed for fast intercity and international transport, road of lower class is designed for transport between districts and urban areas. Finally, municipal roads serve for local transport in urban areas.

on Metrology, as amended (hereinafter, “Metrology Act”) stipulates that a penalty[3] based on certain measurement may be imposed only if verified measuring instrument, which conforms to prescribed legal metrological requirements, was used.
As far as the absence of more detailed procedural rules is concerned, the Czech Constitutional court delivered a judgement in the past, which contains conclusions applicable to weight enforcement as well. For the purposes of legal relations, it is sufficient that public authorities are required to use measuring devices in accordance with the Metrology Act. On the other hand, detailed legal requirements on methods and measuring devices, such as type, model etc., would be contrary to the requirement that laws shall only regulate legal relationships of the legislation addressees.[4]

Both, the LS WIM and the HS WIM, are performed by the owner of the particular road, i.e. either the state, regions or municipalities. In case of the LS WIM road owners cooperate with either Police of the Czech Republic or Customs Administration of the Czech Republic. Furthermore, both, state police and customs administration are competent to perform the LS WIM themselves without involvement of road owners.

The Road Network Act regulates penalties for infringements identified through the LS WIM or the HS WIM. The law recognizes two types of infringements, i.e. offense of the driver and offense of the haulier.[5] Whether the LS WIM or the HS WIM is used, results of measurements are forwarded to the competent authority if any infringement is identified. The competent authority (customs office or municipal authority depending on a category of an offence) conducts initial screening and initiates offence proceedings which may result in penalty. The rights of an accused person, such as the right to present evidence or the right to appeal, are respected throughout the offence proceedings. The maximum penalty for both driver’s and haulier’s offence is 500 000 CZK fine.[6] In case of shortened offence proceedings the driver can be fined up to 15 000 CZK only and by accepting the fine ticket he waives the right to appeal.

2. Metrology Aspects in “WIM direct enforcement”

2.1 Type certification– simulated functional tests

Simulated functional tests are performed when assessing resistance to the influence of the external environment on complete scales unless the size and/or configuration of the scales make it impossible to test them in their complete form. In such cases, testing is allowed with a load signal generator taking the place of load receptors.
The metrological body approving measuring device types can accept a manufacturer's proposal to modify the method and manner in which simulated functional tests are performed, if suitable with regards to the specifics of the technology and design of the scales' measurement chain. [1]

2.2 Tests of resistance to physical effects

- Tests of resistance to random vibrations
- Shock resistance test

[3] Penalty or administrative sanction for violation of rules on maximum gross and axle weight meets the criteria of criminal charge under Article 6 (see the European Court of Human Rights Judgement in Engel and Others v. the Netherlands, No. 5100/71; 5101/71; 5102/71; 5354/72; 5370/72, Series A no. 22, 08.06.1976)
[4] The Czech Constitutional Court decision no. IV. ÚS 868/11 of 1 June 2011 (available at http://nalus.usoud.cz/ in Czech language only).
[5] Offence of the driver is generally based on subjective liability (intentional offence), while offence of the haulier operator is based on strict liability.
[6] The amount equals to 18 000 EUR or 20 000 USD approximately.

2.3 Weather resistance tests

- Resistance to limit temperatures
- Resistance to operating temperatures
- Resistance to air humidity
- Dust and water resistance

2.4 Electromagnetic compatibility (EMC) tests

Resistance to interference caused by power lines, induced by high-frequency fields
During a simulated functional test under the given test conditions, measurement error must not exceed the maximum permissible error or the system must detect a serious error and react to it.

- Resistance to electrostatic discharge
- Resistance to electrical fast transients/bursts
- Resistance to electrical surges
- Resistance to AC mains voltage dips
- Limit power voltages test

2.5 Software

The special care shall be given to legally relevant software (i.e. programs, data, type-specific and device-specific parameters that belong to the measuring instrument, and define or fulfill functions which are subject to legal control)

Resources for securing software subject to metrological verification of measuring devices are as follows:

- Only authorized individuals may be given access, for example using codes (passwords) or a special device (hardware key, etc.); codes must be changeable,
- The measuring device's memory must store all accesses, listing the date of the access, identification of the authorized individual performing the access, and the type of access,
- Memory capacity must be sufficient for at least 2 years of expected accesses; if memory capacity for access record storage is exhausted, no automatic erasure of any stored records can take place,
- It must be possible to recall relevant access records to the full extent of information recorded,
- It must not be possible to erase access records without removing a physical seal,
- Downloading of software subject to metrological verification must be possible only via an appropriate secure interface connected to the scales,
- The software must include identification of its version, which must change if any software version changes occur,
- Functions that are performed or launched via a software interface must meet the terms and conditions of this legislation. [1], [2]

Czech Metrology Institute as the only authority in the Czech Republic for type approval certification and verification has issued from the starting point (year 2010) six type approval certificate for domestic and also for foreign manufacturers. Afterwards some installations were verified. The fact is that in the period from 2010 to 2015 only few of them were used for law enforcement since the legislation rules were not complete. Currently, three HS WIM systems are verified and can be used for weight enforcement in the Czech Republic. One site located in Moravia region and two sites located in Region of central Bohemia. We expect more activities in this field during the year 2017 since the ministry of traffic has announced to initiate a bigger tender for HS WIM systems that will be used on highways and also on selected regular roads.

3. Initial verification – practical results and experiences with HS WIM

In the Czech Republic since 2014 are tree HS WIM system for direct enforcement in operation. Results of initial verification in Tab.1 present the standard deviations intervals of three vehicle types full and half loaded. The initial verification on one of the above mentioned stations has been provided by CMI in co-operation with Transport Research Centre in September 2015.

The results (see Tab.1) of the tests showed that the Standard deviation Interval was slightly more loaded on a static scale most cases resulted in the second axle being significantly heavier during dynamic weighing. The biggest weighing error of the first axle of Vehicle No.2 (half loaded) was between 6,80 – 9,92 % and 3,21 – 7,22% (loaded).

Based on the above measured results the WIM site has been certified for a direct enforcement measuring, which started immediately after one moth verification phase.
We assume that the higher the value of measurement error axles of four-axle vehicles was due to the fact that, with the vehicle axles are independently suspended (terrain version, flat steel suspension).

For vehicles of structure measurements show values typically higher axle variations than conventional road vehicles. [5]

Table 1 - Summary statistics for pre-weighed trucks

Vehicle No. 1 - 2 axles rigid

	Standard Deviation Intervall in [%]	
	full loaded	half loaded
GVW	0.18 - 0.56	0.25 - 1.07
Axle 1	1.64 - 1.85	0.32 - 1.81
Axle 2	2.06 - 2.06	2.39 - 1.86

Vehicle No. 2 - 4 axles articulated lorry

	Standard Deviation Intervall in [%]	
	full loaded	half loaded
GVW	1.34 - 1.53	1.29 - 1.84
Axle 1	3.21 - 7.22	6.80 - 9.92
Axle 2	3.96 - 4.39	2.99 - 3.39
Axle 3	2.66 - 3.72	0.23 -2.39
Axle 4	0.40 -2.64	1.17 - 1.87

Vehicle No. 2 - 5 axles articulated lorry

	Standard Deviation Intervall in [%]	
	full loaded	half loaded
GVW	0.41 - 0.65	2.56 - 0.81
Axle 1	5.67 - 6.03	0.07 - 0.42
Axle 2	3.50 - 4.70	2.43 - 3.06
Axle 3	2.32 - 4.81	0.09 - 1.46
Axle 4	4.31 - 5.14	0.27 - 1.61
Axle 5	4.27 - 3.91	2.12 -2.90

Figure 1 – Vehicle No.2 – Initial verification

The mentioned WIM site position is on a secondary road (parallel to the highway D1 Prague – Brno), with two traffic lanes. The traffic volume of heavy vehicles is aproximatly 600 veh./day .

Table 2 - Statistic of penalized overloading vehicles, penalized on the WIM site II/602

	Overloading in [t]					
	>1 t	>2 t	>3 t	>4 t	>5 t	>6 t
Number of penalised vehicles in one month period	43	16	5	2	2	1

The most overloaded cases are local carriers. They form a full 98 % of all offenses, with practically no foreign carriers. For various reasons were excluded 29 potentially overloaded vehicles, because the validity of measuring were not 100%. [4], [5]

4. Conclusions and recommendations

Although the HS WIM is a part of the Czech legal system for more than a decade, public authorities are far more experienced with the LS WIM. The HS WIM was primarily used as a pre-selection method due to the lack of certified scales in the Czech Republic. Only few years ago the Czech Metrology Institute issued first certificates for the HS WIM system. Near future will show us whether and to what extent the HS WIM became a solid part of weight enforcement in the Czech Republic.
As far as metrological aspects are concerned, the following conclusions may be drawn:

- Validity of measurement must unconditionally create part of WIM systems built in the Czech Republic for the needs of direct recourse.
- Possible movement of load in the place of measurement influences the result of measurement of the weights of axles, however not the total weight of the vehicle itself. The impact of movement of load is significantly lower also as regards a set of axles.
- Accuracy of measurement of the distance between axles of a vehicle

The accuracy achieved by WIM system is ±5cm at best. In addition to that, HS WIM stations should be supplemented with:

- Measurement of position of a wheel in the cross-profile of the lane
- Distinguishing of an independent wheel and wheel set
- Measurement of temperature of the road in the place of sensors. [5]

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DIRECT ENFORCEMENT OF OVERLOAD BY WIM

    

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Abstract

Heavy commercial vehicle overloads contribute to deterioration of infrastructure and increase road unsafety and unfair competition between transport modes and operators. An efficient enforcement system of weights and dimensions at an affordable cost is therefore required. A large scale project was launched by the French Ministry of Transport in 2014 in France, led by IFSTTAR, in cooperation with the Cerema, to demonstrate the feasibility of using high speed weigh-in-motion (HS-WIM) systems for direct enforcement of overloads. This ambitious challenge requires overcoming technological and metrological gaps, and modifying the current legislation. The required tolerances are ±5% for the gross vehicle weight, and ±10% for axle loads for 100% of the vehicles. The methodology is to develop sorting criteria and algorithms, eliminating the outliers, that is to say the weighing data outside these tolerances. The project organization and management is described and the first results are presented in this paper.

Keywords: WIM (Weigh in motion); axle load; gross vehicle weight; direct enforcement; overload; testing; type approval; legal metrology.

Résumé

Les poids lourds contribuent à la détérioration des infrastructures et contribuent à l'insécurité routière et à la concurrence déloyale entre modes de transport et entre opérateurs. Un système de contrôle efficace est donc requis pour faire respecter les poids et dimensions à un coût abordable. Un projet de grande envergure a été lancé en 2014 par le Ministère français en charge des transports en France, piloté par l'IFSTTAR en coopération avec le Cerema, pour démontrer la faisabilité de l'utilisation des systèmes de pesage en marche à vitesse courante (HS-WIM) pour le contrôle automatisé des surcharges. Ce défi ambitieux nécessite de surmonter les problèmes technologiques et métrologiques et d'adapter la législation en vigueur. Les tolérances visées sont de ± 5% pour le poids total du véhicule, et de ± 8% pour les charges à l'essieu pour 100% des véhicules. La méthode consiste à développer des critères et des algorithmes de tri permettant d'éliminer les mesures hors de ces tolérances. L'organisation et la gouvernance du projet sont décrits et les premiers résultats présentés.

Mots-clés: Pesage en marche (WIM), charge d'essieu, poids total, contrôle-sanction, surcharge, essais, approbation de modèle, métrologie légale.

1. Nomenclature

DGITM: General directorate for infrastructure, transportation and sea (Ministry of Environment, Energy and the Sea, in charge of Transport)
IFSTTAR: The French institute of science and technology for transport, development and networks
Cerema: Centre for Studies and Expertise on Risks, Environment, Mobility and Development
GVW: Gross vehicle weight (equal to the sum of all the axle or wheel loads)
HCV: Heavy commercial vehicle
HS-WIM: High speed weigh-in-motion
LS-WIM: Low speed weigh-in-motion
B-WIM: Bridge weigh-in-motion
PDF: Probability density function
WIM: Weigh-in-motion
WP: Work Package

2. State-of-the-art and challenges of direct enforcement

The project builds upon previous research works carried out by IFSTTAR and Cerema on WIM, e.g. the European project WAVE (Jacob 1999 and 2002), and the projects carried out since 1996 for the Ministry of Environment , Energy and the Sea (DGITM) in charge of Transport, allowing the deployment of a National WIM network for overload screening (Dolcemascolo et al., 2015). The project also builds upon a literature survey of International experiences on direct enforcement, to decide what could be transposed or adapted in France.

Today, many countries in North America, Europe and Pacific area, use WIM for overload screening upstream to checkpoints, sorting the suspicious vehicles for a static or LS-WIM check on scales approved by the Legal Metrology (Jacob and van Loo, 2008), (Jacob and Feypell-de La Beaumelle, 2010). The Netherlands and France first coupled WIM systems and video cameras, to identify presumed overloaded vehicles by performing OCR from the licenses plates, and used this to profile transport companies frequently cited. Those with frequent presumed infringements are targeted for warnings and in company checks.

The deployment of direct enforcement by HS-WIM systems, i.e. delivering directly penalties, began in Taiwan in 1998, with large tolerances of 30%, enough to enforce high overloads at that time. After a few years these high overloads disappeared and the direct enforcement was stopped. Later, in 2010, it started again with reduced tolerances, i.e. 10% on GVW. After 2 years, the number of overloads dramatically decreased, and thus the direct enforcement was again suspended. Since 2011 Czech Republic adopted a law authorizing direct enforcement by HS-WIM, with tolerances of ±5% for GVW and ±11% for axle loads. Current statistics show that 65 to 70% of the heavy vehicles are weighed in these tolerances. The first approved systems were installed but some issues remain to be resolved, such as the system reliability, the sorting of vehicles weighed within the tolerances and the implementation of penalties (Doupal et al., 2012).

The DGITM has installed 29 weighing systems (EPM) since 2007 on motorways and main highways, which can identify overloaded vehicles in the traffic flow (Marchadour and Jacob, 2008). These systems are spread all over the country on highly trafficked roads (≥ 1,500 trucks/day). They meet three objectives:

- to preselect suspected (overloaded) vehicles to be checked on a dedicated area with an approved weighing scale (static or LS-WIM) approved in the OIML class 5;

- to target checks in companies from the identified and alleged offending vehicle file;
- to develop regional check plans from the statistical knowledge of traffic;
- In addition, the speed control allows detecting fraud of the speed limiter.

The requirement in France for direct enforcement is getting 100% of the validated measurements within the tolerances of the OIML R134 class 5 (OIML, 2006), or within the confidence interval boundaries of the accuracy class A(5) of the COST323 European specifications of WIM (Jacob et al., 2002). But 100% of the accepted measurements should lay in these tolerances instead of 90 to 95% for non-legal applications. The ±5% tolerance for GVW is currently accepted for static and LS-WIM instruments approved for enforcement.

Increasing this tolerance would likely lead to an increase of overload magnitude due to increase maximum overload limitation, which is currently mostly less than 5 to 10%. It would also not comply with the common practice and legislation in force on overload enforcement. For axle load, the tolerance will be chosen between ±4 and ±8%. However, a HS-WIM system installed on an existing road, cannot weight 100% of the HCVs within these tolerances because of various external factors influencing the measurements, and above all the vehicle dynamics. Therefore to qualify a WIM system, it should identify by itself the vehicles certainly weighed within the tolerances, and reject the other ones, avoiding any risk of penalizing compliant HCVs.

3. Direct enforcement project

The project intends to assess the feasibility of direct enforcement by WIM and to prepare its certification for 5% tolerance. IFSTTAR, with the support of Cerema, is in charge of the technical work packages of the project.

3.1 Project content and organization

The project is organized in five work packages (Figure 1 – Project organization~~Figure 1 – Project organization~~~~Figure 1 – Project organization~~). A central work package (WP1) covers the certification and type approval procedure. Three research and development works packages (WP2 to WP4), and an experimental work package (WP EX) are designed to develop solutions and to test them, feeding the WP1. This WP1 is developed according to the Legal Metrology and International Metrology Laboratory requirements. It will build on the French experience of direct enforcement of speeding, spacing and traffic light crossing. Calibration of the systems, quality control of the measurements, and organizational and legal aspects will be investigated jointly with the DGITM. Detailed functional specifications of the WIM systems will be achieved.

Calibration techniques including automatic self-calibration will be improved and adapted. "Good weighing" indicators based on sorting criteria will be developed to allow a built-in identification of HCVs certainly weighed within the required tolerances.

The WP2 is divided into two sub-packages:
- The WP2.1 analyzes and characterizes sensor/pavement interactions and sensor responses to assess performances and potential of various marketed sensors, by modeling and testing in laboratory and on a test track under controlled conditions, i.e. on a large testing pavement facility. External factors influencing load measurements will be analyzed and their influence reduced or eliminated. First results are presented and discussed in sections 4.1 and 4.2.

- The WP2.2 aims at developing a new optical fiber sensor and WIM system, more efficient and less expensive than current WIM systems.

The WP3 investigates MS-WIM solutions for direct enforcement, including the design of optimal sensor arrays, and above all develops criteria and algorithms for sorting HCVs weighed within the specified tolerances. MS-WIM aims at increasing the proportion of vehicles weighed within these tolerances by coping with the vehicle dynamics.

The WP4, carried out with the support of Cestel, a Slovenian company manufacturing a B-WIM system named “SiWIM”, aims at assessing the capability of a B-WIM system to perform direct enforcement. Concrete frames bridges and orthotropic steel bridges are instrumented and used. Other types of structures (e.g. girder bridges) may also be used.

The WP-EX contains a 18- to 24-month road trial, involving 3 to 4 WIM manufacturers or vendors providing their own systems for testing and improvement or adaptation to direct enforcement. This experimentation is carried out on a major motorway (A4) in eastern France operated by SANEF, a concessionary company. Police, weighing officers and traffic controllers are also involved. The first 4 WIM systems were installed on the A4 motorway in September 2015 and the first tests started in October 2015.

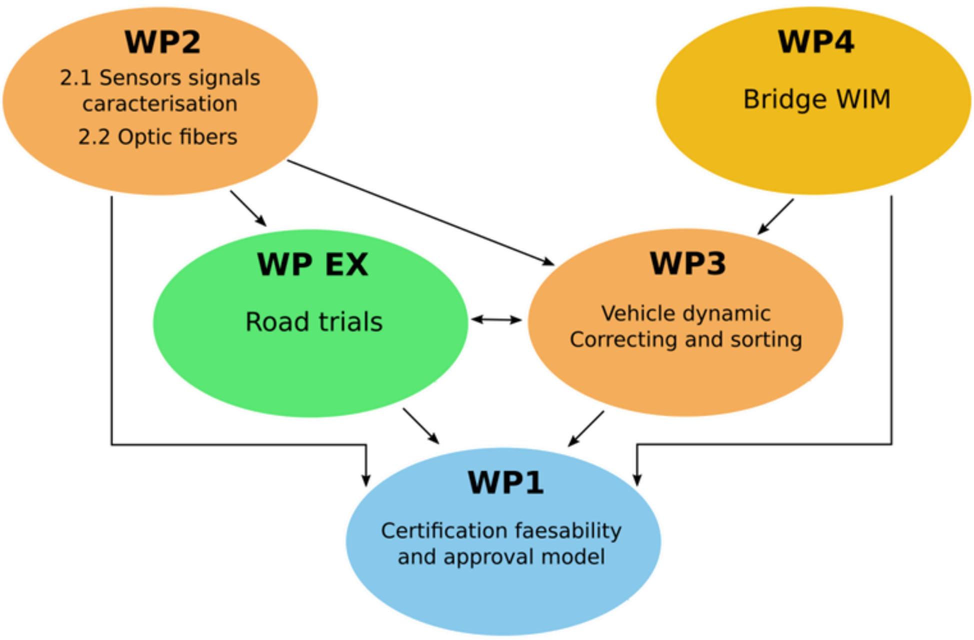

Figure 1 – Project organization and work packages

3.2 Project schedule

The project is divided in two phases of 24 months: the first phase started in January 2014, and will ends in September 2016 after a 8-month extension; it intends testing a preliminary feasibility of direct enforcement by WIM, overcoming technological obstacles, and at an affordable cost, by:

- validating the repeatability and reproducibility of in pavement mounted sensor response, with a suitable signal processing and correction of external factors effects;
- assessing the homogeneous functioning of a multiple sensor array;
- studying the feasibility (cost and performance) of an optical fiber WIM system;

- qualifying a B-WIM system for direct enforcement, with concrete frame bridges and orthotropic steel bridges;
- developing a self-calibration and built-in sorting algorithms to identify the vehicles weighed within the required tolerance;
- setting the principles of a type approval and certification procedure for the WIM equipment's to be used for direct enforcement, according to the specifications.

4. Road sensor solutions (WP 2)

A first major step of this project consists to assess the response and performance of the WIM sensors available on the market, in laboratory and on a test track, under controlled conditions. Sections 4.1 and 4.2 present the first tests performed by IFSTTAR, in the laboratory and on the IFSTTAR accelerated pavement testing facility.

Then these sensors are be tested and improved on road. Both steps should allow to improve the algorithms used for the sensor signal processing, and to select suitable signals to meet the required accuracy and tolerances for direct enforcement.

4.1 Laboratory assessment of WIM sensors (WP2.1)

An evaluation of the electro-mechanical response of the WIM sensors has been carried out in the laboratory. Two types of sensor (piezo-quartz and piezo-ceramic) have been submitted to cyclic loading tests, using a hydraulic testing machine. Two types of tests have been performed, under vertical loading (compression) with the sensor laying on a rigid support, and as a 3-point bending tests. Figure 2 – Test setup~~Figure 2 – Test setup~~~~Figure 2 – Test setup~~ shows the test set up used for the 3-point bending tests on the piezo-quartz sensor. The piezo-ceramic sensor, which has a low stiffness, was placed on a metallic support beam, to carry out the 3-point bending tests. Table 1 - Variations of the piezo-quarz sensor sensitivity vs the loading frequency~~Table 1 - Variations of the piezo-quarz sensor sensitivity vs the loading frequency~~~~Table 1 - Variations of the piezo-quarz sensor sensitivity vs the loading frequency~~gives the variation sensitivity from piezo-quartz sensor versus loading frequency. This variation is about 2%.

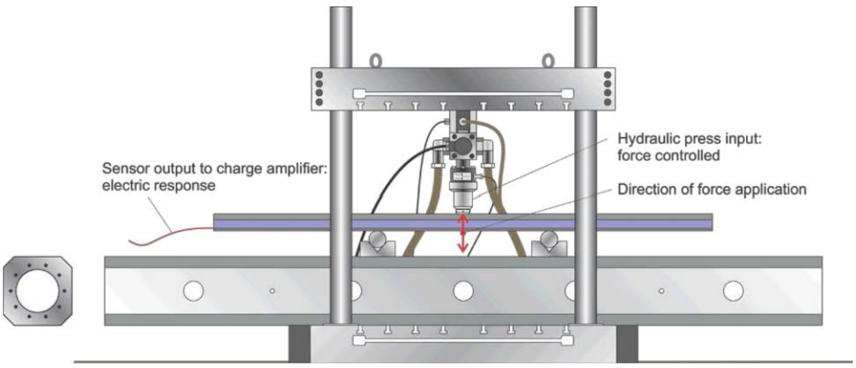

Figure 2 – Test setup

Table 1 - Variations of the piezo-quarz sensor sensitivity vs the loading frequency

Frequency	5Hz	10Hz	20Hz
Max (pC/N)	1,73	1,75	1,74
Min (pC/N)	1,69	1,71	1,69
Average (pC/N)	1,71	1,72	1,72

Standard deviation (%)	1,80	1,30	1,70

4.2 Experiment on the IFSTTAR full scale accelerated testing facility (WP2.1)

The accelerated pavement loading facility of IFSTTAR in Nantes is designed to study damage of real pavements, under accelerated heavy traffic loading (Figure 3). The circular track is 120 m in length (for a diameter of 38 m), the maximum speed is 100 km/h, and the maximum wheel load is 65 kN.

Figure 3 – The accelerated pavement testing facility of IFSTTAR in Nantes.

The experiment was carried out on a thick bituminous pavement consisting of a 7 cm thick asphalt concrete wearing course, over 34 cm of asphalt road base, placed on a granular sub base. The deflection meets the requirements of the class 1 (excellent site) of the COST323 European WIM specifications (Jacob et al., 2002).

Ten WIM sensors, vertical strain transducers and temperature sensors were placed in the pavement, accelerometers were installed on the arms of the pavement testing facility, to measure the applied dynamic loads. Row data have been collected to evaluate the repeatability and the variations (Table 1 2) due to temperature, motion, transversal location, dynamic load, etc. All these tests and results are described by Hornych and al. (ISWIM7-2016).

Table 2 - Variation coefficient (σ/m) from sensor measurements vs velocity

	Velocity (km/h)		
Sensor type	32.4	50.4	72
Piezo-quartz type F (%)	1.21	1.32	1.79
Piezo-ceramic (%)	1.30	1.44	1.50
Number of runs	1580	1580	1580

4.3 Fiber optic sensor (WP2.2)

The use of fiber optic sensors in WIM systems presents many advantages: small sizes, sensibility of fiber optics to physical phenomena in the host medium, static calibration using known mass, immunity to electromagnetic waves interference enabling their deployment in areas where the electronic sensors do not work, finally the electronics for the detection and data processing is simple, compared to the different conventional sensors.

Different configurations have been used to realize WIM systems based on fiber optics:

- Amplitude variations of optical signal due to the attenuation caused by the pressure on the optical fiber deformation, measurement using Bragg gratings sensors installed into the pavement, or the phase variation of optical wave in the fiber optic sensor.
- A polarimetric sensor based on the measurement of phase shift between two orthogonal polarizations in the optical fiber has been developed in the project WAVE.
- The birefringence has been created in the fiber using an external pressure, but the sensitivity to the temperature variations has limited its performance.

Research work is carried out on the realization of a polarimetric sensor with low sensitivity to temperature. The first step was to find and analyze the behavior of birefringent optical fiber, with low sensitivity to temperature. Figure 4 shows the birefringence variations of different birefringent optical fibers as a function of the temperature. An optical fiber with elliptical core has the smallest birefringence depends on the temperature variations.

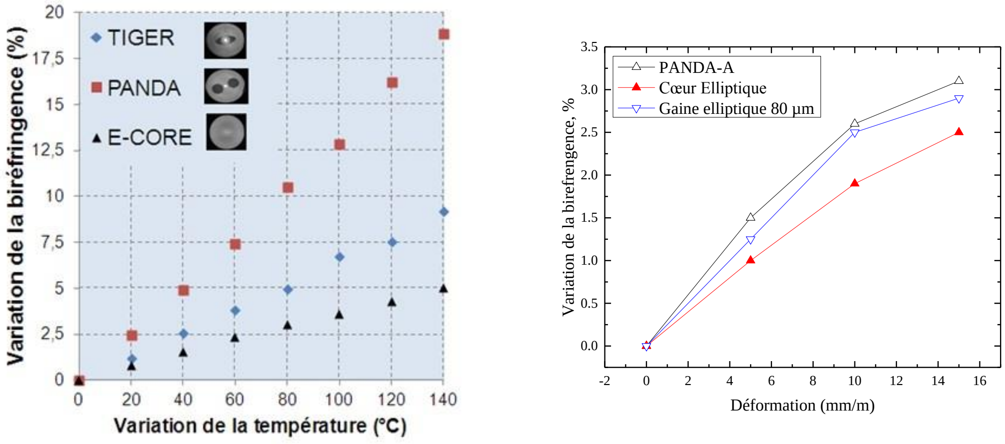

Figure 4 – Variation of birefringence vs temperature and deformation

Currently the realization of the optical set-up is in progress and laboratory tests will validate the choice of the optical fiber. The interrogation technique is in development to obtain a high performance system.

5. Road trials (WP-EX)

The aim of road trials tests is to validate, with reference test vehicles, traffic vehicles and in controlled current traffic conditions, the functional and metrological ability of the WIM systems to be used for direct enforcement. The objectives are to demonstrate the technical and metrological performances of the measuring instrument on site.

Testing and assessing new algorithms will be done by constructing one or more prototypes of WIM system integrating all required functions for direct enforcement.

The trial site is located on the motorway A4 (Figure 4 – Overview of the road-test site in Saint-Avold (A1 motorway)~~Figure 4 – Overview of the road-test site in Saint-Avold (A1 motorway)Figure 4 – Overview of the road-test site in Saint-Avold (A1 motorway)~~), with 2x2 carriageways, near the toll-gate of Saint-Avold towards Metz to Strasbourg in eastern France operated by SANEF, a concessionary motorway company. This motorway is currently trafficked by HGVs and is equipped with a high speed WIM (HS-WIM) equipment for screening presumed overloaded vehicles upstream of a control area fitted with a type approved static weighing system. Test trucks can make one loop in 35 minutes, i.e. at least 8 runs per day.

The WIM systems were installed in September 2015 and the first tests were done in October 2015. More than fourteen weighing sensor lines have been installed including ten from three suppliers (Sterela, Kapsch, Fareco). All row data can be collected and analyzed. Additional sensors can detect truck transverse location, temperature, pavement deflexion, etc. Accuracy class A(5) has been reach during the three calibration days. More details about the site, installation and first results are given by Klein et al. (2016).

Figure 4 – Overview of the road-test site in Saint-Avold (A1 motorway)

6. Bridge WIM (WP4)

Bridge weigh-in-motion (B-WIM) uses the deck of a bridge as a scale in order to assess axle and vehicle weights of heavy vehicles. The concept was first introduced by F. Moses in the late 1970s in the US. A more efficient algorithm has been developed in the WAVE project, still based on the least mean squares but with a global optimization method. It makes it possible to assess at once the vehicle speed, the axle spacing and weights. Later, algorithms have been proposed to take into account the lateral location of the loads on the bridge deck, using influence surfaces. This makes it possible to apply the concept to bridges where the lateral behavior is not uniform or not linear (e.g. girder bridges and orthotropic decks).

The aim of this WP is focused on the improvement and making reliable the recorded on integral bridges signal processing, in order to eliminate measures out of the enforcement tolerance, and on the research of a better adapted algorithm for orthotropic steel deck bridges. A B-WIM system have been installed on the French motorway A1 near Senlis, also operated by SANEF, with 2x2 carriageways. This new “SiWIM” was developed by Cestel and has been tested on this bridge in July 2015. The weighing sensors (extensometers) are fixed under the bridge deck while a camera is mounted on a mast along the traffic lane on the bridge to catch the truck license plates and pictures (Figure 5 – B-WIM: sensors mounting and camera~~Figure 5 – B-WIM: sensors mounting and cameraFigure 5~~). This allows to identify the truck suspected of being overloaded for pre-selection. Accuracy class B(10) has been reached.

Figure 5 – B-WIM: sensors mounting and camera

7. Certification, type approval, initial and in-service verifications (WP1&WP3)

One of the key challenges of the project is to develop certification and type approval procedures of WIM systems, adapted to direct enforcement. The statistical approach of the European specification COST323 cannot be used for such a legal purpose, as stated in its scope. 100% of the measured and identified as overloaded vehicles by the system must be with the metrological tolerances, i.e. ±5% for the gross vehicle weight, and 4 to 8% (to be defined) for the axle load. The OIML R134 recommendation will be used (OIML, 2006).

Moreover, to be approved by the Legal Metrology, the system should not provide any measurement outside the MPE (maximum permitted error), and therefore should double check and either corrects or eliminates doubtful or uncertain measurements, using any relevant criteria to be developed in this project. The criteria may be based on an analysis of the dynamic behavior of the vehicle, e.g. identifying large variations of the vertical acceleration and tire forces, or runs out of the lateral tolerance of the weighing sensor, or even by an in-depth analysis of the raw signal delivered by the sensor compared to a database of reference signals, such as those recorded on the large testing facility in Nantes (section 4.2). The choice of the relevant sensors and system design and architecture will depend on the ability to comply with these requirements. Simulators and models of heavy vehicles will be used to carry out digital simulations and to check these procedures.

8. Conclusions and perspectives

Direct enforcement by WIM is a very challenging objective and requires a series of significant steps forwards and progresses, both in WIM technology and in its implementation, operation and certification. This project mainly addresses the technological and scientific issues, but also, as a central issue, the metrological aspects of certification and type approval.

A strong partnership with WIM manufacturers and vendors is implemented in this project as the companies already developed their own know-how and have a great field experience. Combining their technology and the scientific R&D efforts of IFSTTAR and Cerema, we hope to successfully address this great challenge, and contribute to a better compliance of heavy commercial vehicles weights and dimensions in the future.

Acknowledgements

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BRAZILIAN PIAF MODEL AND THE DIRECT ENFORCEMENT PROJECT





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Abstract

The paper presents the data used to design the model about Automated Integrated Weigh Station (PIAF) as well as three instrumented pavement technology for direct enforcement. The PIAF model includes a Control Station Runway (ECP), precision measurement runway and control of escape station that automated enforcement inspection in Operational Control Center (OCC). The pavement structures for performance evaluation in conjunction with the weighing equipment, specifically in ECP are sized in Continuously Reinforced Concrete Pavement (PCCA), Bituminous Pavement Modified by Polymer (PBEP) and Conventional Bituminous Pavement (PBEC).

Keywords: weigh in motion; WIM; direct enforcement; continuously reinforced concrete pavement; modified asphalt; weigh sensors, PIAF.

Resumo

O trabalho apresenta os elementos utilizados para concepção do modelo de Posto Integrado Automatizado de Fiscalização (PIAF), além de três tecnologias de pavimento instrumentados para fiscalização direta. O modelo PIAF contempla uma estação de controle em pista (ECP), medição de precisão e controle de fuga que, em conjunto, realizam a fiscalização automatizada através de um Centro de Controle Operacional (CCO). As estruturas de pavimento para avaliação de desempenho em conjunto com os equipamentos de pesagem, especificamente da ECP, são dimensionadas em pavimento de concreto rígido continuamente armado (PCCA), pavimento betuminoso espesso modificado com polímero (PBEP) e o pavimento betuminoso espesso convencional (PBEC).

Palavras-chaves: pesagem em movimento; WIM; fiscalização direta; pavimento rígido continuamente armado; ligante modificado; sensores de pesagem, PIAF.

1. Introduction

The Brazilian highways have been affected by the economic growing. The traffic volume of commercial vehicles operating on roads has increase due to the growth of the economy. Given this fact, the weight control is fundamental to preserve the structure of the road pavement, whereas in part there is the overloading of vehicles. The proposition of a new weigh station model and evaluation of different types of pavement are goals of cooperation agreement between the National Department of Transportation Infrastructure (DNIT) and the Federal University of Santa Catarina (UFSC) through the Laboratory of Transport and Logistics (LabTrans).

2. Brazilian PIAF Model

The definition of the Automated Integrated Weigh Station (PIAF) architecture aims to reduce human intervention as best as possible, as well as the execution of processes that involves the supervision of transit and transport in heavy vehicles. The PIAF must aggregate the latest operational and technological innovations and best practices to meet existing challenges in the best possible way. For this, the model has incorporated in its design the concept of pre-selection at the directive of the highway speed bearing, using as a basis the weighing technology on the move at high speed (HS-WIM: High Speed Weigh-In-Motion), Automatic Reading of Plates (LAP), and vehicle classification and recognition. Likewise, includes the performance of traffic officers from Operational Control Centers (OCC), enabling remote operation and in real time from one or more jobs simultaneously.

2.1 Automated Integrated Weigh Station (PIAF)

The Automated Integrated Weigh Station (PIAF) is an automated surveillance unit and modular, which allows performing a series of inspection procedures and data collection in the areas of traffic and security. This consists of three basic units, such as Control Station Runway (ECP – *Estação de Controle em Pista*), Escape Control Center (CFP – *Controle de Fuga em Pista*) and Inspection Station (PF – *Posto de Fiscalização*). Figure 1 shows the PIAF and presents the supervisory devices with its features.

The units that make up the PIAF have the function to carry out the supervision and control of the heavy vehicles that travel the highway. In this context, the ECP performs the pre-selection of all vehicles with any possible irregularity such as overweight or oversize. In the stretch of highway before the PIAF, the road signs should indicate to drivers about the area of supervision. In the case of highways with more than one line, lorries must, obligatorily, to keep in the right-hand lane before the ECP to the entrance of the checkpoint, in addition, the area around the ECP to the checkpoint must have segment with its controlled access.

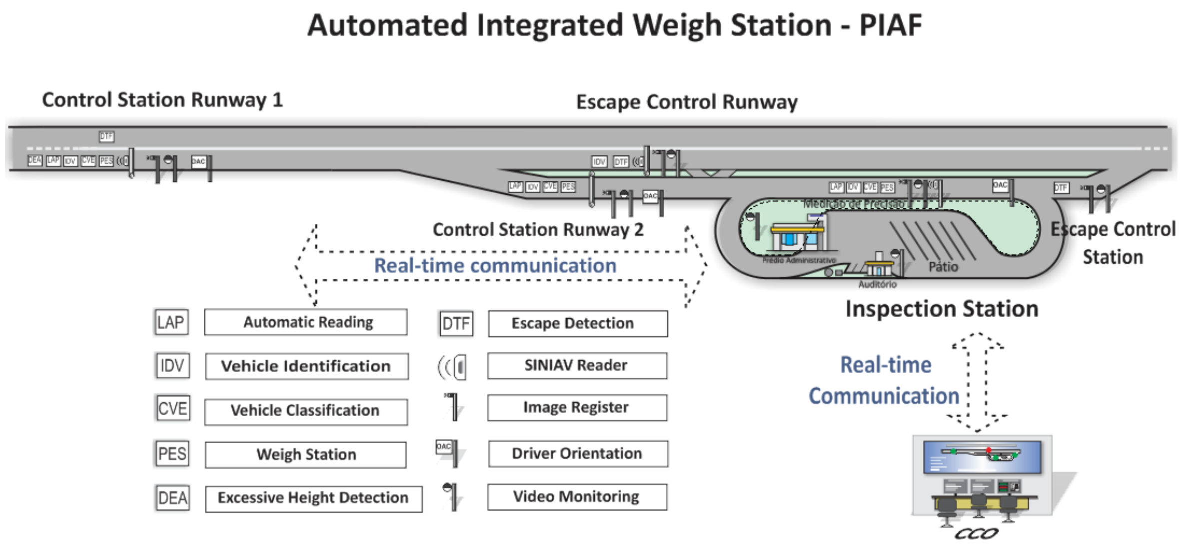

Figure 1 - Automated Integrated Weigh Station (PIAF)

The moment a vehicle passes by ECP, the WIM system collects all the information from covers identification as well. For any suspicion or irregularity detection, or for some reason the pre-selection is not be performed, the driver will be required to enter in the Weigh Station to be weighted in a precision scale. Calibrated equipment approved by the National Institute of Metrology, Technology and Quality (INMETRO). In addition to the measurements performed in the ECP, the pavement of the main lane is instrumented in order to carry out a data collection of the pavement behavior under vehicle influence. On this process, the pavement deflection response is collected at the moment the vehicle pass by.

A communication device, made with luminous signs, provide the driver the information to proceed to the weigh station (or not), just after ECP and before the weight station entrance, this can be done through variable message panels and/or semaphores. Vehicles which go through the road shoulders, between lanes or by the right lane (not indicated for heavy vehicles), should be properly identified. The main identification are ANPR software and photo. All containing the time of the infraction define by a specific legislation. The same procedure is performed when a vehicle bypass the Weigh Station in attempt to avoid the precision scale measurements. Finally, any attempt of escaping from enforcement the vehicle must be identified by the surveillance system on the station.

At the PF, the vehicles shall be subjected to precision scale inspection and all procedures are monitored by the OCC.

2.2 Ntional road distribution of PIAF

The location of PIAF must be validated accordingly with its functionalities, considering the effectiveness and feasibility of installation. The first step was a verification and analysis of the possible sites to installation. A pre-analysis of the pre-appointed locations, uses a geoprocessing system (ArcGIS) for visual and graphical analysis. To phases are needed to weigh station location analysis. The first phase assessed the existent vehicle Weigh Stations (PPV) uses by DNIT for mobile and fixed enforcement on the federal highway network. In the second phase, the new fix and mobile weigh stations, constant in the public notice 11-

0162/00 called PIAF, which should be evaluated and analyzed. For each of these phases, two main criteria for choice of PIAFs were created, considering both effectiveness and feasibility.

The General Road Operations Coordinator (CGPERT) of the DNIT defines the selection criteria to define when and where to construct the PIAFs. In 1st and 2nd phases, there are two main criteria: 1st criteria: will not be considered in analyzing the a PPV located on highways currently granted and with granting future defined by the Federal Government. 2nd criteria: will not be considered in analyzing the PIAFs located on highways where the total heavyweight vehicles are less than 500 trucks/day. For inclusion or exclusion of any PIAF, both criteria are take into consideration.

A GIS program is than feed with the locations of the pre-selected sites. The information is divided between the two phases of analysis. The data from each location and the information from the govern database are divided using layers. The layers are separated between phases. 1st Phase (existing PPV) and 2nd phase (new PIAF). Types of weighing station (fixed or mobile). Quantity of heavy trucks. Highways Concessions or not. Location and amount from productive sectors in Brazil (sugar, ethanol, copper, nickel, Tin, fuels, pig iron, wood, corn, iron ore, paper, cardboard, steel products and soy). Fiber optic communication. In addition, existence of possible escape routes.

With the individual or collective selection of these different layers, it was possible to generate maps for review and decision on the PIAFs. All maps contain the title of the corresponding layer, the compass, the scale used and the caption of the lines and the points contained in the map. The data about the current conceded highways and future concessions have been provided by the National Agency of Terrestrial Transports (ANTT). Figure 2 present a map locating all stations from 1st and 2nd phases (fixed and mobile), in conjunction with the highways marked with the greatest volumes of heavyweight vehicles.

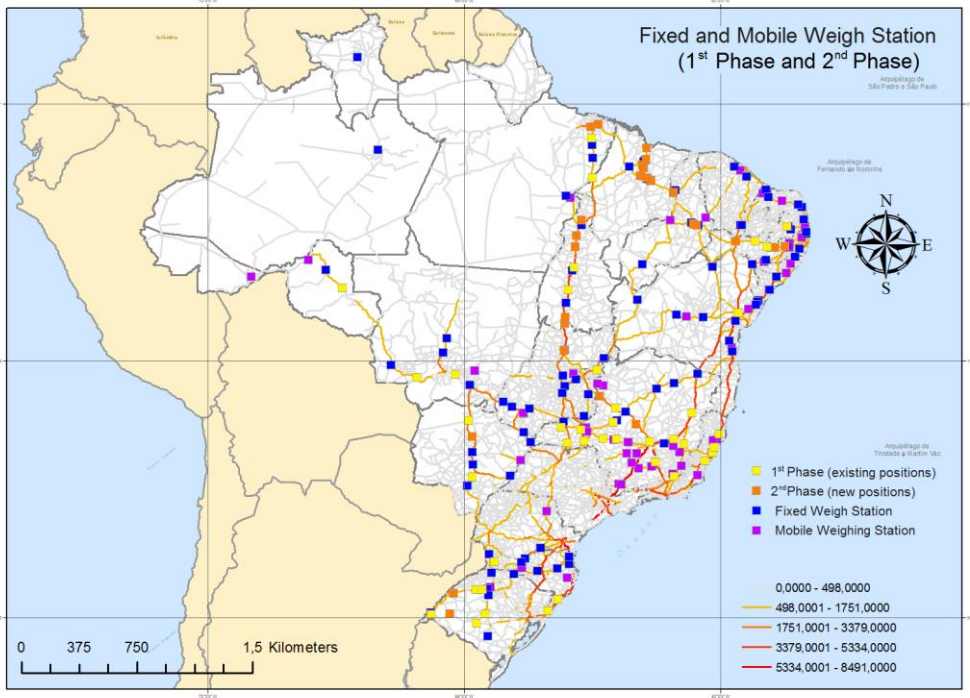

Figure 2 - Fixed and mobile PPVs (phases 1 and 2) with the volume of heavy trucks

Most of the stations located along the highways with the greatest volumes of heavy trucks, which travel on exporting or importing products. The PIAF locations are concentrated in the South, Southeast, Midwest and Northeast of Brazil. Grouping the PIAFs around regions, such the points in the map, there are areas in the North of the country with the lower concertation of PIAF stations, mainly because the volume of heavy vehicles on that road is less than 500 trucks per day. There are a large number of vehicles coming to deliver in the ports than coming from it. That is way most of the PAIF are located near the coast and less in the countryside.

2.3.Projects of Automated Integrated Weigh Station(PIAF)

The PIAF design project establishes the premise of infrastructure adopted should ensures durability during the life cycle and ensures continuously effectiveness and performance features. The design took into account to the recommendation stablish at specifics standards, manuals, instructions, and quality control. The geometry of the road around the ECP must meet the criteria defined as Class I at the COST 323 (1999), which defines the sit as excellent for WIM systems.

The pavement structure chosen for the ECP is a continuously reinforced concrete pavement as recommended in the method and orientation of the Continuously Reinforced Concrete Pavement manual from FHWA (2009). The parking lot area is design using an Interlocking Concrete Paver, working as a more ecologic solution. The acceleration and deceleration lanes and precision measurement are both design using a concrete pavement slab with dowel bars and rebar mesh. The experience gained during the years of operation of weigh stations showed how susceptible are those sections of pavement to the effect of acceleration and deceleration of vehicles.

The accommodation of vehicles in the courtyard and the access handles that give passage to the parking courtyard will be scaled so that the Loading Vehicles Combinations (CVCs) does not have accessibility problems. The legislation governing the requirements necessary for the movement of CVCs is resolution No. 68 of 9/23/1998, of the National Transit Council (CONTRAN). This legislation stipulates that the CVC can't introduce total gross weight exceeding 74 tons and its length must not exceed 30 meters. For the study in question the inter-links of articulated seven axes (BT7), road-train of nine axles (BT9), “Romeo and Juliet” of seven axes (BTL), multiple trailer of seven axes (CA) and the truck Stork (CG), were considered.

The precision scales and the concrete slab design at the influence area of the scale are between the responsibilities of the contracted party. In this way, materials specifications, design, execution and maintenance will depend on the type of equipment selected to operate at the PF.

The administration building at the PIAF shall meet the requirements of law No. 10098, of 19 December 2000, and the NBR 9050:2004, which defines accessibility to Buildings, furniture, urban equipment and Spaces as regards technical parameters to be observed for the assistance to persons with disabilities or reduced mobility. The criteria for the access ramps must agree with recommended as well as doors openings and circulation areas throughout the entire building.

3. Direct Enforcement Project

To achieve success in projects of direct supervision is necessary for the performance of the components required for this purpose is in constant consonance and the knowledge and use of new technologies assist in this process. The equipment of weighing sensors need to be installed on specific pavements, that meet the proper standards for correct functioning, and in the same way all the WIM equipment should collect data properly.

The project COST 323 (1999) has defines standards and specification for WIM systems using either pavements or bridge structures. In relation to the type of pavement, the COST defines features for identify structural characteristics divided by classes. The minimum required class for direct enforcement using WIM systems for high speed is Class-I, see characteristics in Table 1.

Table 1 - Parameters for installation of WIM systems Class I (COST 323, 1999)

PARAMETERS FOR INSTALLATION OF WIM SYSTEMS - CLASS I	
Maximum longitudinal slope	≤ 1%
Maximum cross slope	≤ 2%
Radius of curvature (more possible tangent)	~ ∞ m
Permanent deformation (3 m beam)	≤ 4 mm
Pavement deflection (Benkelman beam 13t)	≤ 20 (10-2) mm
Pavement deflection (FWD 5t)	≤ 15 (10-2) mm
Roughness by index IRI (m/km)	≤ 1.3

3.1 The pavement structures

In order to search for new solutions of road pavement structures that meet the conditions of the weighing system in motion for direct supervision, it is performed a proposal of three solutions of instrumented floors. These decks are designed to follow the assumptions and concepts defined for the new model of post quoted in item 1.1 getting thus technological knowledge to present alternatives aimed at improvements in the management of the infrastructure of the weigh stations under jurisdiction of the DNIT.

The experience acquired in 2008, were installed 64 weighing sensors (quartz, ceramic, polymer and optical) on a station built with standard floor and allowed to infer that the floor used in Brazil did not submit necessary features to meet the requirements of WIM systems. It was proposed three new solutions: Continuously Reinforced Concrete Pavement (PCCA); Bituminous Pavement Modified by Polymer (PBEP); and Conventional Bituminous Pavement (PBEC).

2.2.1 Continuously Reinforced Concrete Pavement - CRCP

The Continuously Reinforced Concrete Pavement (CRCP – in Brazil called "*Pavimento de Concreto Continuamente Armado*" – PCCA) respects the guidelines for design and construction of the Federal Highway Administration manual: Continuously Reinforced Concrete Pavement Design & Construction Guidelines (FHWA, 2009). This type of pavement allows the continuation of load transfer, without cross-joints due to the continuous longitudinal steel. The structure of the profile for the PCCA is shown in Figure 3.

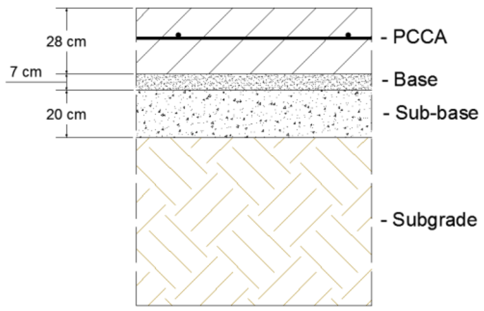

Figure 3 - Continuously Reinforced Concrete Pavement

The amount of longitudinal steel was determined in steel bars 25 CA-50 (25 mm) spaced at 23 cm and 135 cross armor steel bars CA-50 (16 mm) spaced at 100 cm.

2.3.2 Bituminous Pavement Modified by Polymer - PBEP

The sizing of Bituminous Pavement Modified by Polymer (PBEP) is performed through the methodology of French catalog, along with the definitions imposed by COST 323 (1999) a floor suitable for the WIM system. The catalogues are based on empirical and mechanistic analyses that use the highway performance built to interpolate and extrapolate the prediction of the behavior of new projects. The principle of the mechanistic basis of catalog is the assessment by means of a mechanical model compared with the results of the characterization laboratory material (mainly with regard to fatigue resistance and stiffness). In this model, the features of the behavior of materials and traffic and, as a result, are evaluated levels of deformations and stresses subjected to this structure. In short, the method looks for the best combination of technical solutions (type of structure, materials) and project requirements (strategy, traffic, and climate).

The COST 323 (1999) specification defines that, for class I of WIM system, the maximum deflection should not exceed 20x10-2 mm, as shown in table 1. Using computational methods of scaling (for example, Viscoroute) for the maximum deflection, a platform must have a minimum strength of 120 Mpa. For this reason, it was necessary to use a reinforced layer of soil-lime in the base. Given this, the features for the PBEP include structural pathways (“*Voies du Réseau Structurant”* - VRS); record class 3 asphalt (GB-3); class 3 support platform (PF3) and; heavy vehicle fleet of 30 million tickets equivalent axle (TC7). With these characteristics, the catalog of sizing indicates a structure with a surface layer "Couche of Surfing" (CS) based on three layers of treated bases (GB). So, it was defined a structure with 6 cm of bearing layer added to the 10 cm layer of high module (minimum set by COST 323 to the link layer) and a total of 31 cm treated base layer (10 + 10 + 11 cm), as shown in Figure 4.

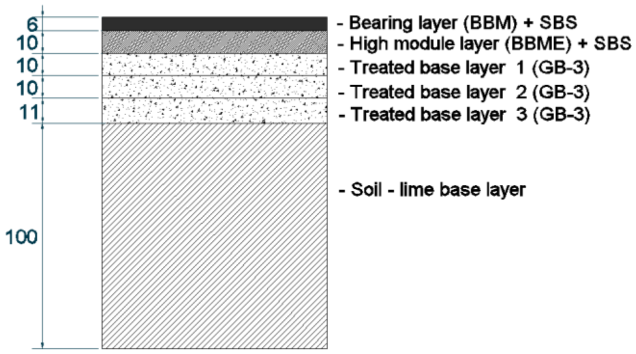

Figure 4 - Bituminous Pavement Modified by Polymer

The binder set is the CAP 30/45 modified with polymer SBS (Styrene-Butadiene-Styrene) and the percentage of asphaltic concrete layers ligand GB is based on manual table of design of bituminous mixtures of LPC (2007) specified in at least 4.2%. Already the other layers the binder is content of 5.5%.

2.3.2 Conventional Bituminous Pavement - PBEC

For the sizing of Conventional Bituminous Pavement used the results of laboratory tests to define the French particle size, thickness of concrete and asphalt binder content of researches of high module (Module Enrobé Élevé - EME) of Quintero (2011) and the base mixture treated (Grave-Bitume - GB) Almeida (2013). The parameters used for the dimensioning of this section considered traffic class TC6 (heavy) with 5.000 vehicles/day; coefficient of 1.0 aggressiveness; standard shaft 130 kN; annual growth rate of 3.5%; project period 10 years; risk coefficient 10% and Poisson coefficient 0,35. Defined, so the floor thicknesses with 6 cm layer of bearing with 5,5% of CAP 30/45; 12 cm thick asphalt mixture with 5,5% of CAP 30/45; 24 cm of gravel base graduated with 4,2% of asphalt binder; 30 cm of sub-base of gravel graduated and the last metro of the sub-ground treated with 5% of cal.

3.2 The location

The construction site of the experimental station with WIM sensors for direct supervision is in the city Ararangua, located in Santa Catarina, a state situated in southern Brazil, specifically on highway BR-101 km 416. Figure 5 illustrates the location of the three types of pavement (section I PBEC, section II PCCA and section III PBEP), next to the Vehicle Weigh Stations (PPV) the DNIT.

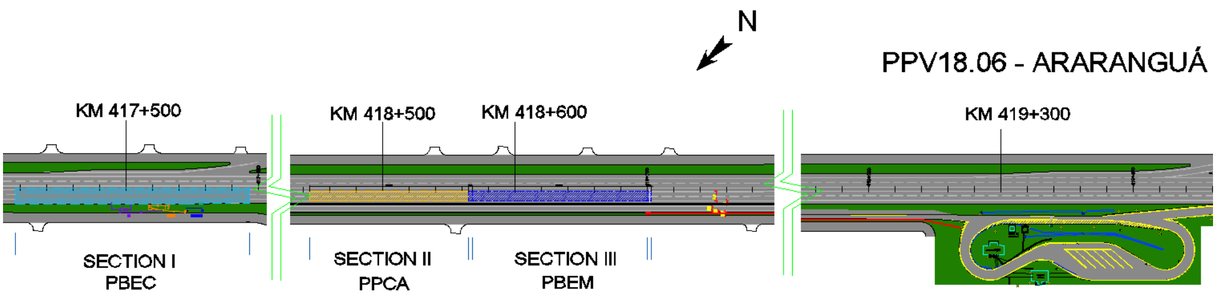

Figure 5 - Location of the three types of pavement in the experimental station

Each floor technology has the extension of 120 m, 70 m and the 20 m finals reserved for the area of influence of the sensors, while the central 30 m are reserved for the installation of weighing sensors and deflection sensors. In addition, between the 2nd and 3rd section are reserved 15 m for transition slab in order to avoid problems with the thermal dilation and discomfort.

3.3 The instrumentation

The development for improvement of weighing in motion with a focus on direct supervision converges to the good performance equipment, deck and operation. In this line, the experiment with WIM systems is to reproduce the basic functionality required in the project whose function is the control of heavy vehicles directly on the highway at speed directive, as shown in Figure 6.

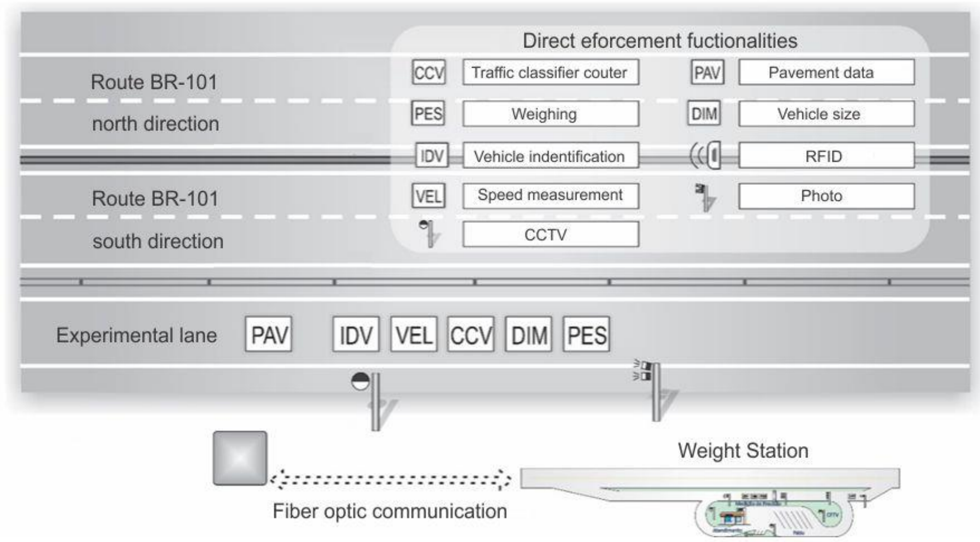

Figure 6 - Features for direct supervision systems WIM

The model, which encompasses the instrumentation of weighing sensors with peripheral equipment for surveillance, as illustrated in Figure 7.

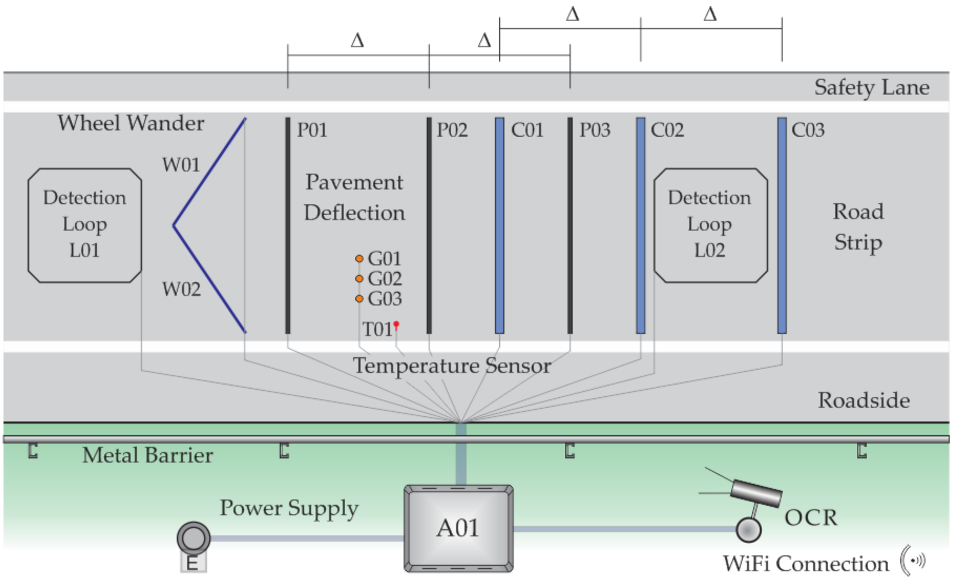

Figure 7 – Equipment installation for direct supervision

The W represents the polymer sensor in order to detect the position and identification of shot; P polymer sensor for weighing; the sensor C ceramic; T temperature sensor; L detection loops; and G the Geophones. In addition to these items, you will find the data acquisition system and camera OCR.

3.4 Conclusion

Currently, 35 Automated Integrated Enforcement Weigh Stations (PIAF) are already tendered and contracted with forecast for operation in 2017. The next step is to cover 27 more posts in this new format of checkpoint across the country. In relation to three types of floors to direct surveillance instrumented, the section it was built in 2013 by starting the new process of assessing the performance of the weighing systems moving at high speed, using as reference data collected at Vehicle Weigh Stations (PPV), provided by DNIT. The model of operation follows the standards previously developed solutions for companies, both in terms of how sensors in terms of integration. Currently, these solutions are under evaluation, adaptation and improvement front conditions and peculiarities, which were found during the operation. In addition to these facilities, the experimental station in Araranguá has an OCC, along the lines of PIAF, in which simplified way reproduces the operation from a distance in order to assess the demand of transmitted information and test the integration of different technologies installed on the station with their pavement technologies.

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WEIGH-IN-MOTION SYSTEMS FOR DIRECT ENFORCEMENT IN POLAND



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Abstract

In 2013 the authors of this article initiated a group within the Intelligent Transportation Systems Cluster which brought together Polish government offices, universities, research institutes and commercial companies, whose goal is to apply Weigh-in-Motion systems for direct enforcement. Implementation of this idea is subject to the two conditions: defining detailed procedures for legalization and metrological control of WIM systems, and defining technical requirements for such WIM systems. This paper presents concepts, formulates problems that require solutions, and shows the current state of work undertaken for this purpose in Poland.

Keywords: Weigh-in-Motion systems, direct enforcement in Poland, legal metrology.

Résumé

Les auteurs de l'article ont initié en 2013 la création en Pologne d'un groupe réunissant les administrations nationales, les écoles supérieures, les instituts de recherches et les sociétés commerciales. L'objectif de ce groupe était de mettre en œuvre les systèmes de pesage en marche à des fins de contrôle sanction automatisé. Ce papier présente les concepts en jeu, présente les problèmes qui ont dû être réglés, ainsi que l'état actuel des travaux effectués en Pologne dans ce domaine.

Mots-clés: Weigh-in-Motion, Systèmes administratifs, métrologie légale.

1. Introduction

Recent developments in Intelligent Transportation Systems suggest that we are close to application of Weigh-in-Motion systems for direct mass and axle load enforcement. In many countries preselection WIM networks already exist and are waiting to be used this purpose. In Poland, 120 WIM sites were built on national roads and this weighing network is going to be expanded in future. Since 2013, actions aiming towards the application of WIM for mass enforcement have been the objectives of the working group within the Intelligent Transportation Systems Cluster, which, beside AGH University of Science and Technology (AGH - UST), includes the Central Office of Measures (COM), the General Inspectorate of Road Transport (IRT), and the companies Kistler, Kapsch Telematic Services Sp. z o.o., CAT Traffic Sp. z o.o., and TRAX Elektronik.

Further in this section, issues related to the development of road traffic and the problem of overloaded vehicles in Poland are discussed. In the second section, selected formal and technical aspects related to the use of WIM systems for direct enforcement are presented. Additionally, a discussion of two basic formal problems, that is the method of expressing the accuracy of such WIM systems and the process of their calibration, is presented. The third section concerns technical issues whose solutions dictate the application of WIM systems for direct enforcement. In particular, the results of studies of the influence of the number of sensors installed at the weighing station, the pavement temperature, and the speed of the weighed vehicle on weighing accuracy are presented. In the final section, requirements and recommendations regarding equipment and algorithms for WIM systems for direct enforcement are outlined.

The necessity of using WIM systems for enforcement stems from two evident reasons:

- the low effectiveness of the currently used vehicle weight control system,
- the high costs incurred in Poland for the development of road infrastructure and the consequent need for its protection from the devastating effects of overloaded vehicles.

The accession of Poland and nine other countries to the European Union in 2004 and the subsequent expansion of the Schengen Area resulted in an escalation of migration and, consequently, an increase in transit traffic in Central and Eastern Europe. As follows from the latest General Directorate of National Roads and Motorways (GDNRM - GDDKiA) report, the average traffic on Polish national roads increased by 84% in 1995-2010, while the contribution of heavy goods transport vehicles with trailers increased over 3.5 times (Opoczynski 2010). It is estimated that approximately 15% to 30% of all trucks are overloaded (Rys et al. 2015). Overloading causes permanent deformations of roads, such as ruts, cracks or wearing course losses. The scale of this problem in Poland is presented in the annual Report of the GDNRM Department of Studies on the technical condition of the national road network (Radzikowski & Forys 2015). As follows from this report, 61% of national roads are in good condition, whereas 39% require different types of repair, of which 13% (2,724km) require immediate repair. On this basis, it was estimated that financial resources needed for modernization and maintenance of roads in 2015 amounted to 1.6 billion EUR.

The applicable Polish regulations concerning the permissible Gross Vehicle Weight (GVW) and maximum permitted vehicle axle loads have been defined in (Minister of Infrastructure 2002). Without going into details, the maximum GVW of the heaviest vehicles, i.e. articulated vehicles with more than four axles, must not exceed 40.0 t, while the maximum static load on a single axle must not exceed 10.0 or 11.5 tonnes on selected roads.

For control purposes, portable static scales are commonly used in Poland. The body authorised to carry out such controls is the Inspectorate of Road Transport (IRT). There are approximately 600 IRT inspectors and 300 vehicle weighing stations equipped with portable static scales but also weighbridge platforms and Low Speed WIM scales (vehicle speed up to 5km/h). Each inspected vehicle is stopped and diverted to a weighing station. Such a procedure takes at least one hour, which makes the system ineffective. Static scales, weighbridge platforms and LS-WIM are subject to legal metrological control, according to the Ordinance of the Minister of Economy. For the purpose of that control the Central Office of Measures - Polish National Metrology Institute (COM) applies a modular approach, according to the OIML R-134 Recommendation (OIML 2006).

In the context of the considered problems, WIM systems for direct mass and axle load enforcement would be the key elements of a road protection system and ensure elimination of overloaded vehicles from the roads.

Practical implementation of this idea is subject to the following conditions:

- defining detailed procedures for the legalization and metrological control of WIM systems (test conditions, reference values used during the calibration procedure, calibration frequency),
- defining the technical requirements for enforcement WIM systems.

2. Legalization and Metrological Control of WIM Systems Used for Direct Enforcement

The problem with the legalization procedures arises from the specific properties of a WIM site, where a section of pavement becomes a part of a system. This means that WIM systems cannot be examined in a laboratory, under controlled conditions. Another major issue arises from the properties of load sensors, which cannot be calibrated in a static way (the pre-weighed vehicles method is not approved by National Metrology Institutes).

2.1 Accuracy Assessment of Enforcement WIM Systems

There are no commonly approved ways to express WIM system errors. The procedure proposed in COST 323 seems to be very informal and requires a series of assumptions regarding the WIM site (Jacob et al. 2002). Some parameters for calculations are taken arbitrarily depending on the conditions under which the experiment was performed. These are the drawbacks and this procedure may not be used in legal metrology. Another accuracy assessment method was described in (Slavik 2008). The author makes assumptions on the distribution of errors, based on a small population of measurement results, and in the assessment process utilizes synthetic data obtained from simulations based on the assumed distribution. This is the major weakness of the presented approach because distribution of the errors should not be assumed to be normal. The most reliable method seems to be that proposed by ASTM (ASTM 2009).

To solve the problem with the legalization and accuracy assessment of WIM systems, COM is working on a new procedure for legalization of Enforcement WIM systems in Poland (Burnos & Ossowski 2015). At the same time, new methods of accuracy assessment of WIM systems have been proposed by AGH – UST. To evaluate the accuracy of WIM system two criteria were proposed: a 95%-percent relative error and a reliability characteristic. The 95-percent relative error is defined as the value below which the errors obtained in 95% of experiments are contained (Gajda et al. 2007), (Burnos et al. 2007). The reliability characteristic $\Phi(\delta)$ is defined by relation (1) and describes the probability of the occurrence of an error with the value greater than δ.

$$\Phi(\delta)=1-P(\delta) \qquad (1)$$

where:

δ - the absolute value of relative measurement error of the GVW or static axle load in the tested system; the error was related to the static measurement result,

$P(\delta)$ - cumulative distribution function of the error δ.

There is an obvious relation between the $\delta_{95\%}$ error and the characteristic (1), namely the $\delta_{95\%}$ error is the argument value for which $\Phi(\delta_{95\%})=0.05$.

The characteristic (1) shape provides more comprehensive information about the system accuracy than a single value of $\delta_{95\%}$. For example, in Figure 1 two characteristics are shown with the same value of $\delta_{95\%}$ = 0.06 (6%). Distinguishing between these systems based solely on the error $\delta_{95\%}$ value would be impossible. Taking into account the shape of the characteristic, one can easily classify these two systems and find that the system 1 accuracy is better than accuracy of system 2.

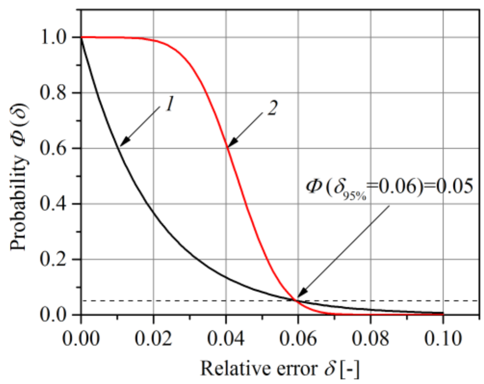

Figure 1 – Examples of reliability characteristics

The strong point of this proposed method is that it does not require any assumption about the type of distribution of errors or about measuring conditions. There is also no need to supplement, in an artificial manner, the experimental data with results acquired by means of computer simulation. This procedure allows easy comparison of two different WIM systems. The reliability characteristic provides additional information, e.g. that the system maximum error does not exceed 10%, or that about 40% of vehicles are weighed with an error smaller than 2%, etc. It therefore enables better interpretation of the quality of the developed and assessed system.

2.2 Calibration of Enforcement WIM Systems

In WIM systems used for direct enforcement, the problem of calibration increases further due to the close correlation between weighing accuracy and the effectiveness of eliminating overloaded vehicles from traffic. It results from the fact that the allowable values of GVW and axle loads must be increased by the amount of the weighing error. Thus, the higher the weighing error is, the fewer overloaded vehicles will be eliminated from traffic. In order to ensure the effectiveness of a vehicle weight control system, the weighing error of WIM systems for enforcement should be at the level of 2%. This value corresponds to the accuracy of static scales currently used for enforcement.

On-site calibration of WIM systems is normally performed using the pre-weighed vehicle method. The GVW and axle loads of these vehicles are reference values during this process. Weighing results obtained from WIM systems are compared to the reference values and on that basis the system calibration coefficient is determined or its errors are exposed during reverification. Fulfilling the above defined requirement for WIM systems accuracy (2%) for system calibration requires the use of mass and axle load etalons with uncertainties not exceeding 0.5% ÷ 1%. Determining the reference vehicle GVW with the required low uncertainty is possible by means of a weighbridge platform, but a more difficult task is to determine the reference static axle load. This problem is illustrated in Figure 2. The graphs show the distribution of the relative error of axle load measurement obtained using static scales. During the experiment, two different vehicles with four degrees of load (GVW) were used. The total number of weighing results amount to 280 and 200 for vehicle 1 and 2 respectively. Dashed vertical lines represents the lower and upper bound of permissible error for a static scale (1%).

a) b)

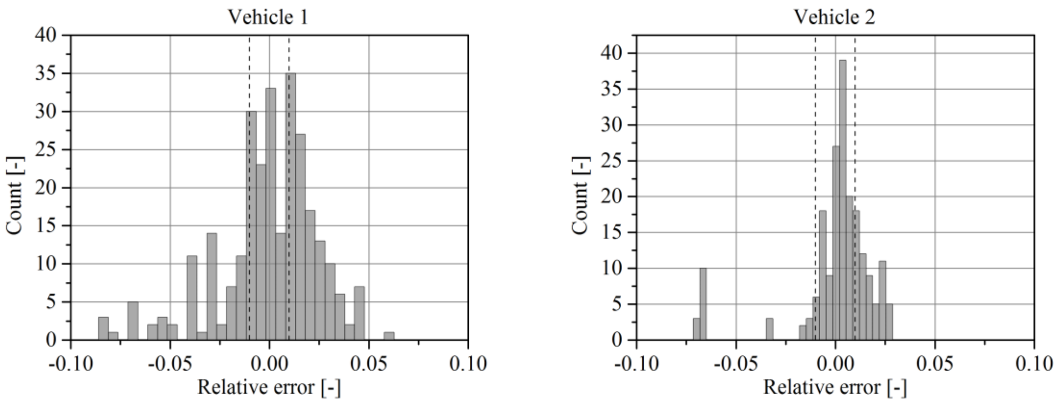

Figure 2 – Random variation of single axle load measurement results from a static scale a) for vehicle 1, b) for vehicle 2

The characteristics in Figure 2 show that in many cases measurement error is outside the permissible range of 1% for static scales. Moreover, error distribution depends on the reference vehicle class, regardless of the scales being used. The reference axle load value should be therefore determined as a mean value from at least of 100 measurements performed under the same conditions.

Another issue related to the accuracy of calibration procedure arise from the fact that the pavement temperature and vehicle speed are the significant influencing factors on the weighing results. In our second paper at ICWIM7 we show (Gajda & Burnos 2016), that precise, Multi-Sensor WIM systems intended for enforcement should be calibrated and tested over a wide range of temperature variation similarly as they are currently tested over a wide range of vehicle speeds (the pre-weighed vehicle method). It is therefore necessary to reconsider views about the method of WIM system calibration and assessing their accuracy using the pre-weighed vehicle method proposed in COST 323 (Jacob et al. 2002).

3. Technical Requirements for WIM Systems Applied for Direct Enforcement

The most important technical requirements for WIM systems applied for direct enforcement concern:

- the number of load sensors and their distances from one another,
- the interference quantities which affect the accuracy of the weighing result,
- determination of the allowed variability subspace of all known interfering quantities. If all these quantities are contained within the determined limits, then the uncertainty of the weighing result is acceptable.

3.1. Influence of the Number of Sensors on the Weighing Result

Increasing the number of load sensors installed in a WIM system brings three essential benefits. It enables the limitation of the influences of random errors and longitudinal inhomogeneity of sensors on weighing accuracy, and the reduction of the system unreliability. One factor that should be taken into account is the system's cost, which increases approximately proportionally to the number of load sensors. The main source of random errors is vertical balancing of the weighed vehicle. Figure 3 illustrates the relation between relative error of weighing result $\delta_{95\%}$ and the number of load sensors. The characteristic was calculated using MSC Adams/Car multibody dynamic simulation software (MSC 2016).

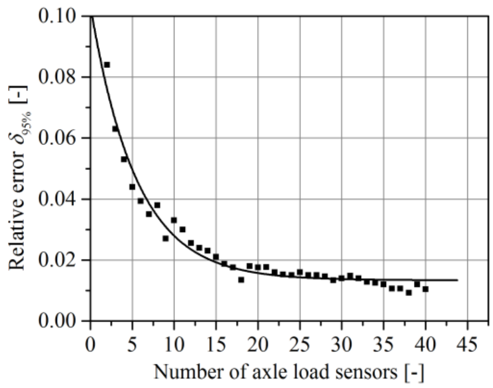

Figure 3 – Dependence of the vehicle weighing result error on the number of load sensors installed in WIM system

This characteristic was determined assuming identical accuracy of all sensors - this does not hold for real WIM systems, particularly after their prolonged operation time due to aging effects. Deterioration of the sensor quality entails an increase in the standard deviation of weighing results obtained with the given sensor. Curve 1 at Figure 4 represents the situation when the uncertainty of all sensors is the same, curve 2 when the uncertainty of each subsequent sensor is 10% greater than that of the preceding one, and curve 3 when the uncertainty increases by 20% from sensor to sensor.

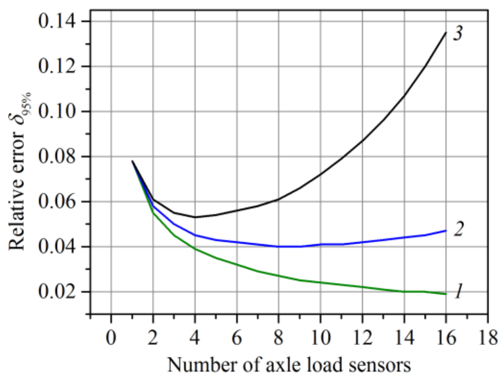

Figure 4 – Dependence of the vehicle weighing result (GVW) error $\delta_{95\%}$ on the number of load sensors installed at the WIM site (curves explained in text)

As follows from Figure 4, in case 2 and 3 the relative error $\delta_{95\%}$ has a minimum for a specific number of sensors. After exceeding the minimum value, a further increase in the number of installed sensors results in the increase in the MS-WIM system error value. The rule "the more load sensors, the better" does not hold in those cases. It is, therefore, justified to eliminate from enforcement WIM systems load sensors exhibiting high variability of weighing results.

3.2. Influence of the Pavement Temperature and Weighed Vehicle Speed

The pavement temperature variability is a significant factor influencing vehicle weighing accuracy achieved in WIM systems. This effect is often ignored for quartz sensors while it is observed regardless of the employed load sensor technology. The characteristics in Figure 5a were determined experimentally by means of the reference vehicles method for two WIM sites in Poland. They illustrate the relative weighing results (GVW or axle load) dependence on temperature (for a fixed vehicle speed of 65 km/h). The investigated systems were calibrated at the temperature 10°C. As can be seen from the figure 5a, the change in the weighing result may reach around 50% for polymer sensors and 7% for quartz sensors due to temperature variation within the range -5°C ÷ +30°C.

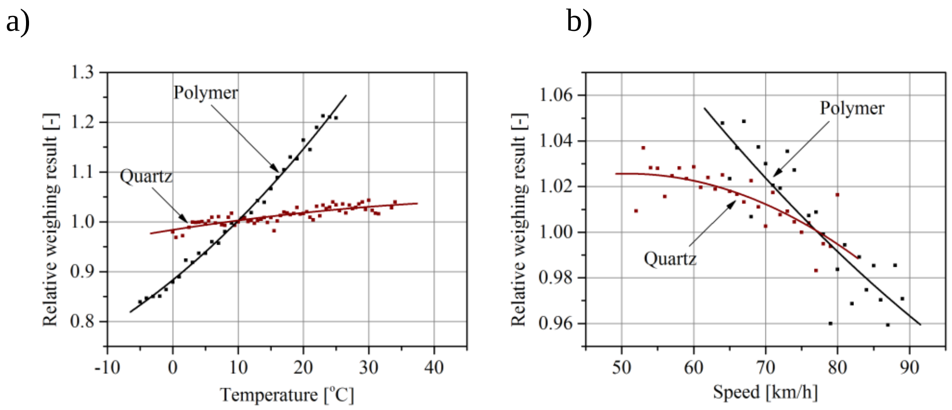

Figure 5 – a) Dependence of the relative result of vehicle weighing on temperature, b) Dependence of the weighing results on the weighed vehicle speed

Achieving accuracy required for WIM enforcement systems entails that the weighing site shall be equipped with pavement temperature sensors and a correction procedure of weighing results should be implemented in the system. Alternatively, the system should be able to perform an auto-calibration, or calibration for several temperature values employing polynomial interpolation between calibration points. These methods are described in (Burnos 2012), (Gajda et al. 2013).

Another observed phenomenon is the dependence of the vehicles' weighing results on their speed. Figure 5b illustrates this effect in the same systems equipped with polymer and quartz load sensors for a fixed temperature range of the pavement (15 ÷ 20 °C). The results shown in Figure 5b indicate that the change in the weighed vehicle speed within the range of 50 km/h to 90 km/h leads to about a 4% change in the weighing result for quartz sensors and 10% for polymer sensors. This exceeds several times the error (about 2%) value which is the condition for effective elimination of overloaded vehicles.

4. Technical Recommendations for WIM Systems for Direct Enforcement

WIM systems for direct enforcement constitute a separate class amongst pre-selection systems. Such systems also feature different requirements concerning the conditions in which they are used, and their technical equipment including sensors and software used to process measurement data. Based on the results of experimental studies and simulations presented, certain recommendations on the construction and application of WIM systems for direct mass and axle load enforcement can be formulated.

Assessment of the accuracy of this class of WIM systems should be carried out on site, and should take into account all interrelated elements. It would appear that there is no valid technical alternative for the pre-weighed vehicle method. The results presented indicate clearly that the module approach is severely inadequate.

Reference values for the masses of such vehicles should be indicated on the weighbridge platform with a margin of error of roughly 0.2%. Axle load reference values should also be indicated in accordance with OIML recommendations, exclusively for two-axle rigid vehicles. The expanded uncertainty of such a reference value should not exceed 1%. Obtaining such a low level of uncertainty requires the calculation of the average of multiple results (from dozens to hundreds of measurements) of weighing operations (compare Figure 2).

Due to the intended use of the results of measurement by WIM systems for direct enforcement, the assumption of a maximum error in the description of the accuracy of such systems is more justified than an error of 95%. Both errors may be determined based on reliability characteristics (1).

Assessment of the accuracy of measurement of mass should be carried out on vehicles of different classes, loaded to different weights, and moving at different speeds, within the wide range of temperatures observed at the site of the WIM system. Experiments should be carried out at different times of the day, or over the course of several days, in order to observe the dependence of the accuracy of measurement on the pavement temperature.

In order to reduce errors caused by balancing of the weighed vehicle, WIM systems for direct enforcement should be equipped with at least 6 lines of load sensors installed in a specially prepared segment of pavement of a length of 250 – 300m.

It is essential to equip WIM systems for direct enforcement with temperature sensors and correction algorithms of weighing results. The characteristic shown (Figure 5a) indicate that temperature correction of weighing results is necessary, regardless of the technology used in the load sensors.

WIM systems for direct enforcement must be equipped with a speed option for the weighed vehicle, and, as is shown by the studies carried out (Figure 5b), with an algorithm for correction of the results.

Summing up the results presented, it can be seen that the accuracy of the vehicle measurement results in the WIM system depends on many factors. Apart from the aforementioned dependence on the vertical balancing of the vehicle, its speed, and the pavement temperature, the dependence of the error on other factors such as wind strength and direction, surface ice, and strength of rainfall should also be considered. Additionally, the class of the weighed vehicle may also influence the weighing result. Without controlling the intensity of these factors at the time when the vehicle is weighed, one cannot determine the accuracy of the result. Therefore, the result is useless from the direct enforcement point of view.

The solution which seems most useful for WIM systems involves experimental determination of multidimensional maps that describe the dependence of error and uncertainty of the weighing results on the influential factors. Such maps will enable users to control the uncertainty of the results of weighing by monitoring the intensity of the influential factors. If the values of these factors as measured during the passage of a weighed vehicle through a WIM site exceed the limits permissible for the required accuracy of weighing, then such results are considered inaccurate and must not be used in enforcement procedures.

5. Conclusions

The paper presents key issues that determine the use of WIM system for direct mass and axle load enforcement. In the light of the presented results it is necessary to revise the views on methods of WIM system calibration. System errors determined from experiments of only several hours' duration, carried out under specific conditions, using pre-weighed vehicles belonging to a limited number of classes, does not describe the system's actual accuracy. Just a couple of hours after termination of the experiment, the error can undergo a significant change caused by the WIM site insulation or by a vehicle belonging to a different class and passing with too low or too high a speed.

For several years, the Department of Measurement and Electronics of the AGH University of Science and Technology in Krakow has been carrying out research into developing an HS-WIM system with characteristics sufficiently good to be directly utilized for enforcement purposes. Concurrently with this research work, the Central Office of Measures has been conducting activities in the area of scientific and legal metrology aimed at developing standards for determining HS-WIM systems' metrological characteristics necessary for type approval, initial verification and re-verification. Since 2013, the above actions have been the objectives of the working group within the Intelligent Transportation Systems Cluster, which includes: AGH University of Science and Technology, the Central Office of Measures, the General Inspectorate of Road Transport, Kistler, Kapsch Telematic Services Sp. z o.o., CAT Traffic Sp. z o.o., and TRAX Elektronik.

Despite the presented difficulties, the authors believe that the technical conditions enabling the use of WIM systems for direct enforcement may be fulfilled. The probability of a positive solution of the described problems has been increased by establishing a special working group. The topics requiring solutions are formal and legal issues, but work is underway and completion is scheduled for 2017.

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Session 8 : Railway WIM

Chair: Louis-Marie Cottineau

IMPLEMENTATION OF RAILROAD WEIGH IN MOTION IN NORTH AMERICA: CASE STUDY DEPICTING BENEFITS OF DYNAMIC CALIBRATION



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Abstract

Freight hauling railroads have been installing a rail-mounted WIM system called a Wheel Impact Load Detector (WILD) on heavy tonnage corridors to improve safe train operations. In North America, Class 1 railroads have installed more than 180 systems capable of identifying defective wheels, improperly loaded cars, and worn-out car suspension components that may affect axle steer ability.

This paper provides a background of the development of the measurement system, its usage, and an overview of the vetting process that was conducted by the Association of American Railroads (AAR) and Union Pacific Railroad to insure that data collected from the intra-railroad network of hybrid WIM systems would be consistently reliable. Guidelines prepared by the AAR for these systems are used as a common standard by all railroads in North America.

Keywords: WILD, Railroad, AAR, Predictive Maintenance, Heavy Vehicles, Freight Transport, Weigh-in-Motion, WIM.

Résumé

Les chemins de fer de marchandises de halage ont été l'installation d'un système de WIM monté sur rail appelé un impact Wheel Charger Detector (WILD) sur les corridors de fort tonnage pour améliorer l'exploitation des trains en toute sécurité. En Amérique du Nord, la classe 1 des chemins de fer ont installé plus de 180 systèmes capables d'identifier des roues défectueuses, les voitures mal chargées, et les composants usés voiture suspension qui peuvent influer sur l'essieu manœuvrabilité.

Ce document fournit un arrière-plan de la mise au point du système de mesure, son utilisation, et un aperçu du processus de vérification qui a été menée par l'Association of American Railroads (AAR) et Union Pacific Railroad pour assurer que les données recueillies à partir du réseau intra-chemin de fer des systèmes de WIM hybrides serait toujours fiable. Lignes directrices préparées par l'AAR pour ces systèmes sont utilisés comme une norme commune par tous les chemins de fer en Amérique du Nord.

Mots-clés: WILD, Railroad, AAR, Maintenance Prédictive, Véhicules Lourds, Transport de Marchandises, Peser-in-Motion, WIM.

1. Background Information Concerning North American Railroad WIM Usage

To aid readers in understanding the benefits and usage of high speed weigh-in-motion for railroads, the next sections provide an overview of certain aspects of the North American system.

1.1 North American Railroads

There are seven Class 1 and over five hundred Class 2, 3, and 4 railroads in North America. This paper focuses on WILD and WILD-WIM usage on the Class 1's, who operate over more than 222,900 kilometers of mainline track. (US AAR, 2016)

1.2 Class 1 Railroad Business Model

A unique feature of North American railroads is that they are privately owned, "for profit" companies. This means that all capital expenditures and maintenance dollars are generated from operating income. The nature of this free market system has resulted in the need to utilize larger freight cars than the freight cars used in many other countries, and to be more efficient and competitive in the marketplace. This also means that each Class 1 owns all of the "right of way" it operates on. Each railroad owns and maintains a significant inventory of the freight cars used in its operation. The railroads and private car leasing companies operate a total of approximately 1.6 million freight cars. All railroads use a uniform specification for design of right of way, rolling stock, and maintenance. This insures compatibility and safe operations when interchanging freight shipments from one railroad to another in the course of conducting business. This standard is specified by an umbrella organization called the Association of American Railroads (AAR). In a manual known as the AAR Interchange Rules, requirements for operation and various equipment maintenance thresholds are delineated (AAR, 2016). In a supplemental set of specifications, the American Railway Engineering and Maintenance Association recommends standards for all of the collective components of the track structure. (AREMA, 2016)

2. Design Features for a Typical Class 1 Railroad

2.1 Track Structure

The US Federal Railroad Administration (FRA) has established the maintenance standards for the US railroad industry track structure. Freight railroad main corridors are maintained to at least FRA Class 5 standards, which allow 130km/hr freight trains and 145 km/hr passenger trains.

To optimize capacity, most mainline routes use a two main track configuration. These parallel tracks are constructed of either wood or concrete ties installed in a well-drained rock foundation known as ballast. The AREMA standard for heavy axle load (HAL) freight trains is based on 32.66 tonne axle loading. Some transcontinental corridors that haul intermodal traffic are built to 35.38 tonne loading standards. A typical 135-car coal train is 2.41 km long and weighs over 17.24 kilotonnes.

Railroads continuously maintain these routes, changing rail, ties, and bridge components and cleaning the ballast so it drains water away efficiently. Track maintenance gangs operate specialized on-track machinery that tamps ballast under the ties to maintain a continuous, smooth running surface.

2.2 Traffic and Maintenance Control Systems

To provide safe and efficient use of the mainline tracks, railroads use a computerized "traffic light" system known as Centralized Traffic Control (CTC). Each railroad links their CTC with software overlay systems that supplement information about specific train makeup with wayside devices such as RFID car identification and a variety of automated freight car defect monitoring systems. A typical railroad utilizes many or all of the following detector types:

- Bearing temperature scanners
- Wheel temperature scanners
- Dragging equipment detectors
- High/wide and shifted load detectors
- Wheel impact load detectors (WILD)
- Acoustic bearing detectors, and
- Wheel profile measurement systems

2.3 Maintenance Facilities

Each railroad has car maintenance facilities centrally located along each major corridor. During the course of a specific train's operation along a corridor, wayside detectors measure and transmit freight car component data into a centralized database to facilitate prompt maintenance and to insure safe train operation. These databases are known as "predictive maintenance" (PM) databases. If a specific defect exceeds pre-set thresholds, and is thereby considered unsafe for continued operation, the detector will then alert the train crew or dispatcher with an instant message to stop the train, inspect the car component, and immediately remove the car from the train.

3. Railroad Industry Collaborates to Improve Safe Train Operations

In 2004, the Railroad Industry formed the ***Advanced Technology Safety Initiative*** (ATSI) to integrate data collected from the network of wayside car defect monitoring systems into PM database search engines used by each railroads' car maintenance planning system. With ATSI, the Industry began a cooperative effort to share all pertinent freight car condition data to improve network-wide train operation reliability and safety. A key facet of this project was to concurrently evaluate disparate wayside detector datasets, with WILD data usage being the primary driver. This integration enabled more efficient planning for car maintenance, and has dramatically improved overall fleet utilization.

The ATSI team and the AAR collaborated to create an AAR-maintained database called InteRRIS. All Class 1 railroads have linked their WILD installations to populate this database with real-time data for all car passes. This allows car owners – both railroad and private, to receive electronic alerts identifying axles with high impact wheel defects. This system has been very effective in facilitating planned maintenance to the fleet, and has resulted in noticeably improved safety and more reliable train operations.

Subsequent to ATSI, the railroads invested in integrated software overlay systems that utilize PM algorithms to plan for scheduled maintenance of cars. This planning is designed to minimize disruption to the primary goal of a transportation company – delivering a customer's shipment on time. These overlay databases are now beginning to process overload, shifted load, and car steering alerts to train crews and dispatchers, further improving safe train operations.

4. Background and Development of the WILD Detector

In the mid-1980's, the WILD system was developed to identify the cause of unacceptably high levels of cracked and broken concrete ties on the Northeast Corridor, a heavily utilized transit route between Boston, MA and Washington, DC. An investigative team from the Battelle National Laboratory provided technical expertise to determine the cause of the tie failures. Auditory analysis of passing trains pointed to wheel tread defects that dramatically increase the vertical force transferred into the rail and tie structure. These wheel defects are commonly called "thumpers". The conclusion from this research is that out-of-round wheel defects are indeed a "root cause" defect that precipitates broken rail, failed bearings, damage to the car lading, and ultimately require the entire track structure to be re-built more frequently. (Harrison, 2016)

An automated data acquisition system was developed to identify defects on the circumference of each rail car wheel. Early installation consisted of four Wheatstone bridge circuits applied to each rail. Each circuit consisted of four strain gages. The strain gages were micro-welded to the neutral axis of each rail, in the space between two ties. Later on, to provide a more complete inspection of the circumference of a wheel, the number of circuits was increased from four to ten. Ultimately, as the filtering process was improved, and the data was leveraged towards providing more accurate wheel and car weights, the number of circuits increased to 16 per rail.

To get a better idea of the destructive forces that wheel defects can generate, understand that while the weight for a typical loaded wheel generates approximately 160.1 kN of force into the track structure; the peak force generated by a five inch 'slid flat' defect [on a freight car travelling at 80km/hr] can exceed 711 kN.

Once the Railroad Industry standardized on the use of WILD for identifying wheels that should be scheduled for removal, system developers began a redesign process to improve reliability of the data acquisition components. These upgrades provide filtering that minimizes the effect of train dynamics on the accuracy of car weights. New capabilities emerged to measure overload, shifted load, and unbalanced load conditions; and worn suspension components that can affect the steering capabilities of a freight car.

5. Union Pacific WILD Statistics

To gain some understanding relative to the scope of usage and benefits provided to a Railroad through leveraged use of WILD, please review the data in Figure 1. Briefly, each day about 250,000 wheels are monitored at Union Pacific Railroad by WILD. Of that total, approximately 255 AAR defects are identified. A high impact wheel becomes an AAR defect when the peak force into the track structure is measured to be 355 kN or greater. For 2015, the defect rate was 0.11% of the total wheel population, resulting in over 35,000 wheel sets being changed.

UNION PACIFIC RAILROAD WILD STATISTICS						
DESCRIPTION	COUNT		ALERT NAME	# ALERTS JAN 2016	# ALERTS FEB 2016	# ALERTS 12 MONTHS ESTIMATED
Number of WILD Detectors	16		Heavy Car (>= 263,001 Overloaded)	30	44	444
			Heavy Truck (>= 263,001 Overloaded)	336	359	4,170
Average Train Speed	40		Empty Car w/Loaded Status	6,476	6,251	76,362
			Truck Hunter	29	73	612
Wheel Population	88,142,660		Front Back Imbalance	24	38	372
			Left Right Imbalance	128	158	1,716
AAR Defects Measured	93,302		Light Car (< 263,001 Overloaded)	15	48	378
			Light Truck (< 263,001 Overloaded)	43	46	534
Wheelsets Changed	34,755					
Percent of Population Condemnable	0.11%					

Figure 1 – Statistics for 2015, with Alerts Extrapolated for 2016

6. WILD Installation Design

The basic components of a WILD consists of the following:

- **Tangent (straight) track for at least ½ the length of a normal train**, in a location where average train speed is approximately 80 km/hr.
- **The elevation (gradient) of the track** should be as level as possible for bi-directional use. For single direction use, a slightly descending gradient reduces coupler tension and generally improves car-weighing accuracy.
- **16 Wheatstone bridge copper strain gage circuits micro welded to the neutral axis of the web of each rail**. (Note the schematic arrangement in Figure 2, below) Each circuit measures the vertical force imparted on the rail in the tie "crib" or space between two ties. This facilitates each wheel being weighed 16 times to identify the average weight and a "peak" weight, caused by a defect hitting the rail.

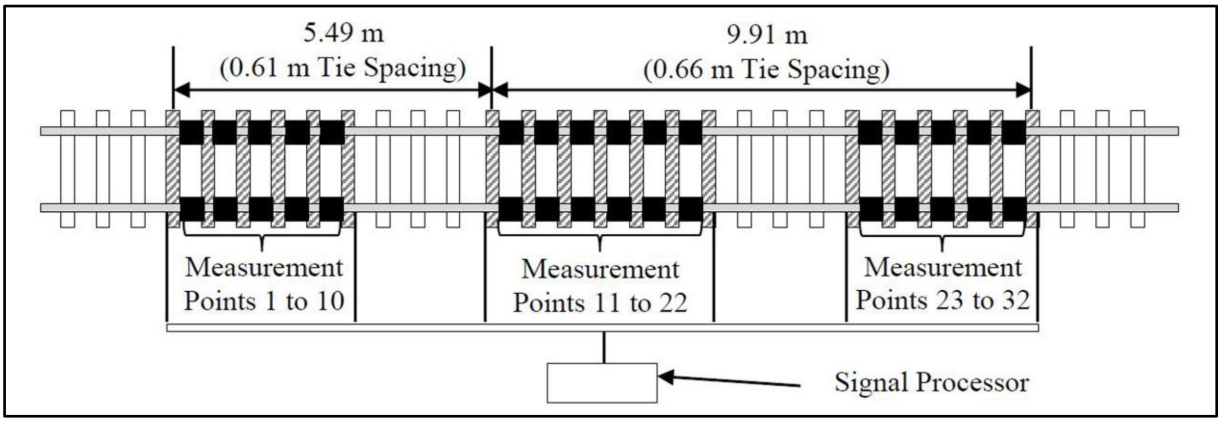

Figure 2 – Schematic Diagram of WILD Circuit Installation (Wood, 2016)

- **Concrete tie spacing** is varied between 61 and 66 cm [on center] to effectively locate any defect on the 360 degree circumference of the wheel. The tie spacing in the instrumented zone is controlled to within plus or minus 3 mm.
- **16 strain gage circuits micro welded to the base of each rail, to measure the lateral force impacting the rail by each wheel**. This measurement is indexed to the largest vertical force obtained by the collocated vertical circuit, and provides data relative to the condition of the suspension components on each car. Worn suspension components can cause an oscillation best described as a "fish-tailing" effect, when the

two axles at each end of the car [in a so-called truck assembly] pass through the instrumented zone. **This is known as "truck hunting".**

- **A 64 channel, high reliability, data acquisition system** that collects individual wheel data, assembles it into axle, truck, and car weights; adding car identification information for each car, then sending all data via TCPIP to the railroad's centralized database.

6.1 Railroad Weigh in Motion Accuracy Guidelines in the United States

Use of railroad WIM weights are governed in the United States by guidelines established by the National Institute for Standards and Technology in Handbook 44. (NIST, 2016) This handbook is the regulation established for all 'legal for trade' measurement systems used in the United States. The handbook section covering railroad WIM is currently predicated on a traditional design for a commercial weighing system – concrete foundation, heavy duty weighbridge, and operating speeds generally less than 24 km per hour.

At the present time, the United States does not adhere to the International League of Metrology specification R-106, which establishes four accuracy classes, each based on the value of the commodity. (OIML, 2016)

AREMA Committee 34 – Scales has an established guideline for verifying the accuracy of 'legal for trade' railroad WIM systems. This guideline is modified as necessary, based on annual changes that may have been made to NIST Handbook 44. The accuracy verification process entails the following:

- A group of reference weight cars is statically weighed on a 'legal for trade' scale whose accuracy has been recently verified with a certified test weight car.
- These reference weight cars are then operated over the WIM system being tested, at speeds consistent with the normal operating speed over the device.
- Compliance to H-44 accuracy is based on whether weight is being calculated for an entire train, or if individual car weight accuracy is required.

For car weights that are used in custody transfer or assessment of freight charges, the AAR Interchange Rules require compliance with AREMA C-34 guidelines for weighing system installation and ongoing performance. Until recently, a device such as WILD-WIM could not be considered for use as a 'legal for trade' system because it was ballast-mounted. Modifications to the guideline are now being prepared that will allow use of ballast-mounted scales in 'legal for trade' applications.

6.2 WILD Development to Optimize Weighing Accuracy

Dynamic interaction between freight cars in trains can affect the weighability for individual cars. To understand this variability, Union Pacific Railroad conducted a series of controlled tests. This testing resulted in development of a dynamic calibration feature designed to compensate for the varying operating conditions at individual installations. Results of the testing are documented in the paper. Site installation design features that enhance equipment reliability and improve car weight accuracy are described in the Conclusions section of this paper.

6.3 WILD Calibration and Ongoing Monitoring for Compliance

6.3.1 *Static Calibration Method for WILD*

Each of the 16 vertical circuits is statically loaded with a calibration fixture that clamps to the rail and applies vertical pressure to the rail with a [capstan-style] screw jack. A calibrated load cell, using the site's data acquisition computer, monitors the pressure applied to the rail. Each circuit is loaded to 13.61 tonnes, which is more than 80% of the weight of a loaded freight car wheel.

6.3.2 *Ongoing Monitoring for Compliance*

The AAR Interchange Rules mandate a quality control procedure to insure that the network of WILD systems reporting defects to InteRRIS provide ongoing accuracy. An algorithm built into the data acquisition computer checks the integrity for each circuit at the beginning and end of each train pass. If the results of this check do not meet the following three criteria, the data set is flagged as not being AAR compliant, and is not used for defect removal until repairs have been made to the detector.

- Static calibration must be done according to the manufacturer's procedures at installation and, at a minimum, once every three years thereafter.
- A minimum of 70% of the 16 circuits must pass a pre-measurement check for [circuit] integrity. (more than 11 circuits)
- The average vertical weight for all wheels measured must be calculated for each active circuit. The range variation (maximum-minimum) of these average weights for a rail must be less than 6.8 tonnes for any train containing 50 or more axles. If the range is greater than 6.8 tonnes, then the data for that rail does not meet validation requirements.

6.4 WIM Accuracy Verification Test

A test plan was prepared to demonstrate the accuracy of WILD weigh-in-motion to Senior Management at Union Pacific. This plan had several goals: the first was to demonstrate how proper installation minimizes train dynamics by reducing coupler tension; and the second was to determine whether data filtering, (known as dynamic calibration) based on speed and weight, tightens the accuracy band for a specific device location.

6.4.1 *Test Site Information*

The WILD used for the verification test is located near Ogallala, NE. This is a two track, concrete tie mainline, with approximately 30 loaded coal trains operating on eastbound Track 2 each day. The track is on a 0.5% descending gradient, and is tangent (straight) for about 2 miles in each direction. The site is located less than one day's travel by train from the Southern Powder River Basin (SPRB) coal mines.

6.4.2 *Control Data for Vetting Accuracy of the Test Site*

Control data for the test consisted of individual car weights from 18 train loads of coal from 3 mines, gathered over the course of one week. Each mine uses legal-for-trade Class 3L weighing systems, with accuracy that is verified bi-annually via testing in accordance with AREMA C-34 test parameters. Collection of car weight data was simplified because the car weights were already being transferred to the railroad for waybilling purposes.

6.4.3 *Dynamic Calibration Procedure For the WILD at Test Site*

Twenty coal cars were weighed for use as "reference weight" cars. Each of the car weights was in the vicinity of 129.7 tonnes. The cars were weighed on a railroad-owned Class 3L weighing system located at Union Pacific's Bailey Yard in North Platte, NE. Prior to weighing the cars, the accuracy of this reference scale was verified with a monitor car.

A special test train transported the 20 reference weight cars to the test site. The train conducted weighing passes in both directions over the WILD in four speed ranges (32.1 km/h, 48.2 km/h, 64.3 km/h, and 80.4 km/h). There were 3 train passes in each direction, for each speed range.

Salient Systems, the WILD vendor, conducted a regression analysis on the weight data. They generated a biasing factor to compensate for weight inaccuracy in each weight and speed range. The data acquisition computer [control] software was updated to include a dynamic calibration table. The bias factors calculated in the regression analysis were added into the calibration table.

7. Comparison Test Between the Mine Control Weights and the WIM

Over the course of two weeks, weight information from three mines in the Southern Powder River Basin was used as control data to verify accuracy of the WIM (with the dynamic calibration enabled). On a random basis, weight information from 18 trains was downloaded from the detector and compared to the weights provided by the mines for "assessment of freight charges" purposes. The results from those comparisons are depicted in the following histogram.

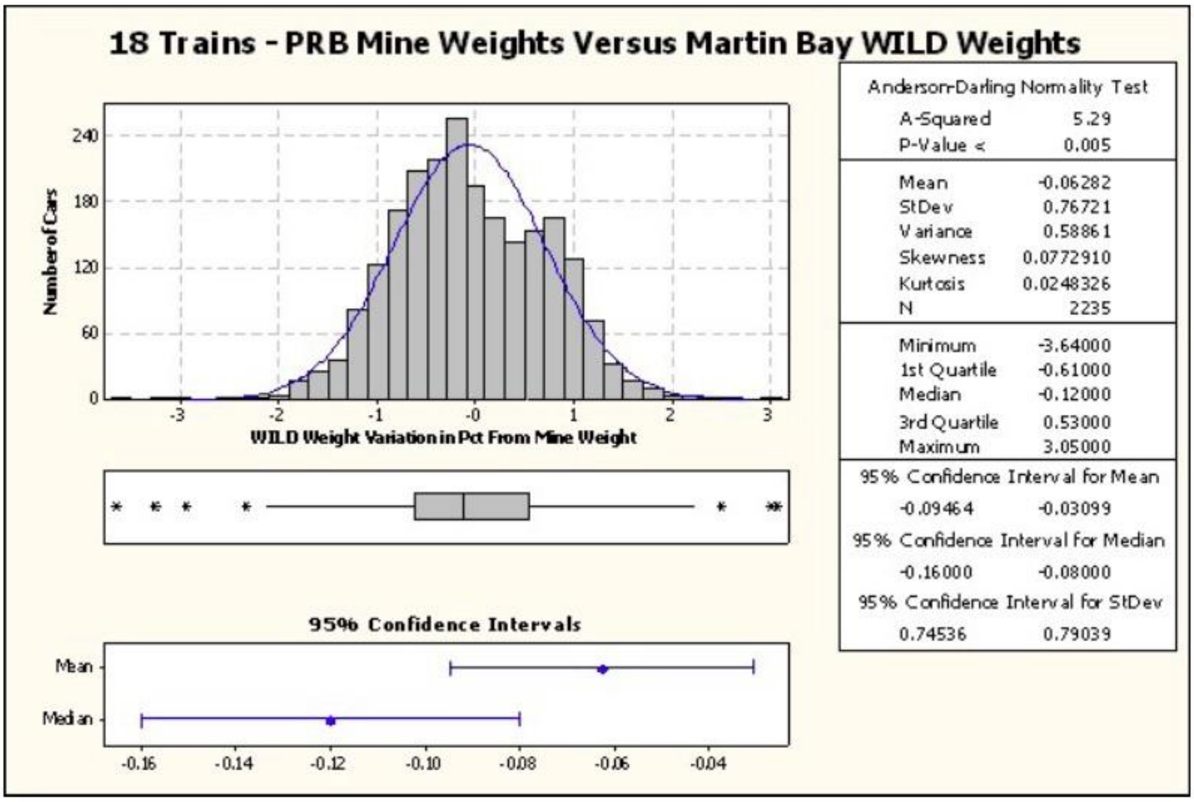

Figure 3 – Dynamic Calibration Test Results Depicting Car Weight Accuracy Variations

More than 95% of the WILD weights were within 2.0% of the control weights from the 3 mines. The mean variation for the 2,235 weights was -0.06%.

7.1 Verification of Weighing Accuracy at Other UP WILD Installations

To compare accuracy of WILD installations calibrated via static calibration versus use of a dynamic calibration; weight data was collected from the network of detectors (16 sites) on Union Pacific railroad. Weights obtained from legal-for-trade weighing systems and WILD weights obtained during the same loading cycle were compared. This query was executed twice; the first during January through March when the support structure of the track may be frozen, i.e., stiffer subgrade conditions; and a 2nd time during May through September. The first data set contained over 215,000 records, and the 2nd data set contained more than 400,000 records. Figure 4 separates the accuracy comparison, based on whether the cars were deemed to be loaded or empty. The result shows high repeatability, and that changes to the support structure that may be caused by frozen subgrade does not affect accuracy. It also shows that use of a dynamic calibration can improve an individual sites' weighing performance by as much as 40%.

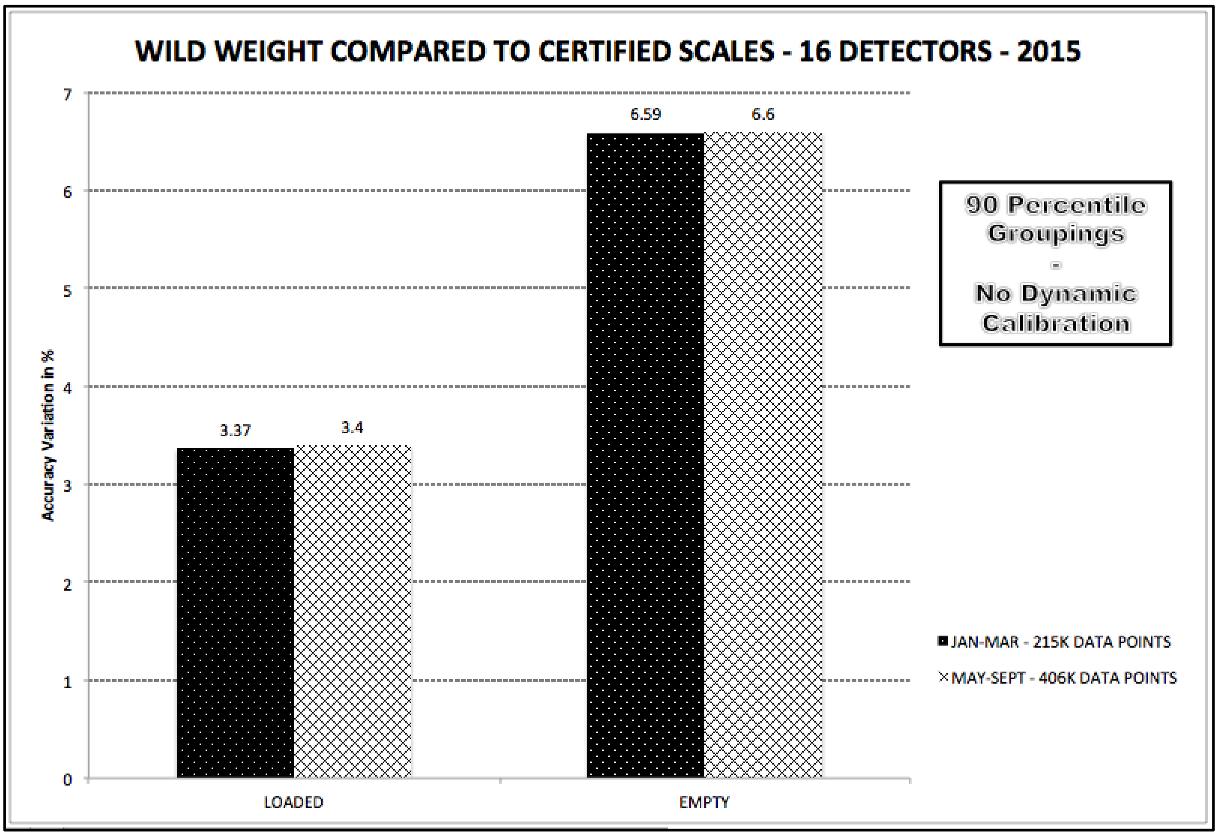

Figure 4 – WILD Car Weights Versus Certified Car Weights – No Dynamic Calibration

8. Conclusions

The results from the Union Pacific testing support the thesis that WIM accuracy for WILD detectors can be improved when the longitudinal forces in the couplers between freight cars is reduced. The graph in Figure 5 shows that resistance, [or coupling force] between adjacent cars is reduced to zero at a train speed of 88 km/h, on a descending grade of 0.5%.

The 2nd premise supported by the test results, is that each potential site location for a WILD-WIM will have a unique signature, relative to the dynamic forces caused by car weight, train speed, curvature and grade of the track. Conducting a dynamic calibration in the manner described in 6.4.3 can compensate for these dynamic forces thru use of a correction table built into the WILD software. When the dynamic forces are minimized, the variability that may be caused by uneven track surface is reduced, as shown in the +/- 2.0% bandwidth in Figure 3.

9. Recommendations Relative to Enhanced Usage of WILD Weigh in Motion

In the author's opinion, test results showcased in this paper substantiate expanded use of a properly calibrated WILD-WIM to improve safe train operation and protect a railroad's investment in its track infrastructure. With the understanding that the network of WILDs is essentially "built out" already, consideration should be given to evaluate the unique dynamic characteristics of each installation by conducting a dynamic calibration, then applying a 'calibration offset'; a feature that is optionally available for all installations.

While accuracy requirements [for Class 3L legal-for-trade devices] mandated by NIST Handbook 44 may not be currently attainable with a WILD; the results of tests conducted during this research may warrant a discussion to consider adoption of the International League of Metrology's OIML R-106 performance specification for Automatic Rail Weighbridges (OIML, 2016). R-106 allows four accuracy classes: 0.2, 0.5, 1.0 and 2.0 percent. While the time investment with regulators at NIST to affect this change will be substantial, a properly installed and calibrated WILD may be capable of meeting the 2% class, providing significant benefits to the railroad industry.

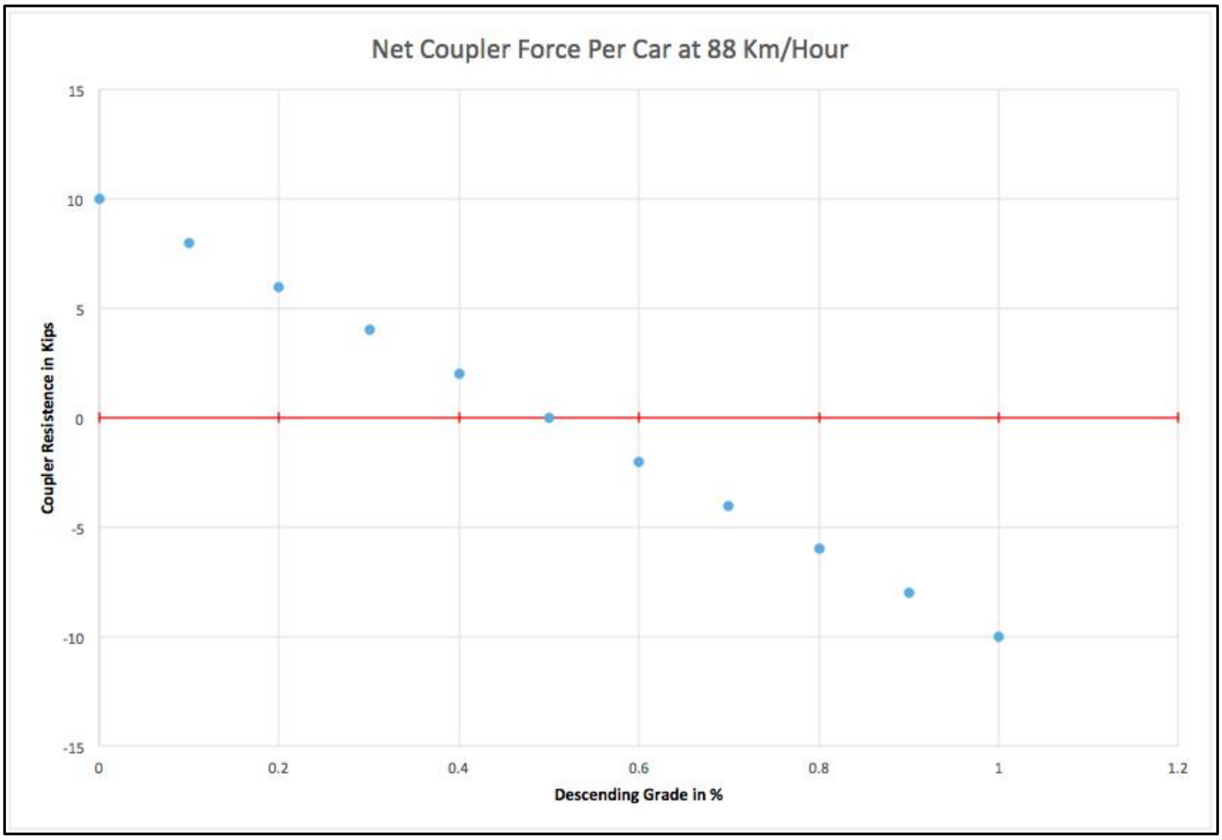

Figure 5 – Coupler Force Between Cars on a Descending Grade, per Davis Equations

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ADAPTING BRIDGE WIM TECHNOLOGY TO RAILWAY BRIDGES

    

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Abstract

The paper provides an overview of the development of a railway bridge weigh-in-motion (B-WIM) system, accomplished within the European Commission financed research project Bridgemon. A steel truss bridge in Poland was used for testing the system. Four trains that passed over the bridge were pre-weighed in a rail yard in Warsaw. The conventional road B-WIM system was adapted to calculate the weights of the train carriages using the measured response from the test bridge and the accuracy of the system was assessed. Initial result showed that weights of one of the four trains of known weight were predicted very accurately, while the wagon weights of the other three trains deviated by as much as 30% from their actual values. The large errors were directly correlated to the changing velocity of trains. The standard B-WIM algorithm, which assumed a constant velocity during the passage of a vehicle or train, was adjusted to allow for the effect of this changing velocity. The results improved dramatically, with the vast majority of the calculated wagon weights falling within 5% of their actual values. Further developments tailored the B-WIM algorithm for weighing trains, including the system interface that employs graphics of locomotives and wagons.

Keywords: accuracy, B-WIM, measurement error, train, weigh-in-motion

Résumé

Le document donne un aperçu de l'utilisation du système de pesage en marche par ponts instrumentés (B-WIM) appliqué au chemin de fer, réalisé au sein du projet de recherche de la Commission européenne BridgeMon. Un pont en acier en Pologne a été utilisé pour tester le système. Quatre trains qui passaient sur le pont ont été pesés dans une cour ferroviaire à Varsovie. Le système B-WIM routier classique a été adapté pour calculer le poids des trains en utilisant la réponse mesurée à partir du pont instrumenté, et la précision du système a été évaluée. Le résultat initial a révélé que les poids de l'un des quatre trains de poids connu ont été prédits avec une grande précision, alors que le poids du wagon des trois autres trains présente une erreur de 30% par rapport à leurs valeurs réelles. Il a été révélé que des erreurs importantes sont en corrélation directe avec la vitesse changeante des trains. L'algorithme B-WIM standard, qui suppose une vitesse constante pendant le passage d'un véhicule ou train, a été ajusté pour tenir compte de l'effet de ce changement de vitesse. Les résultats ont été beaucoup améliorés, la majorité des résultats présentait une erreur de 5% par rapport aux valeurs réelles. D'autres développements ont été réalisés pour adapter l'algorithme B-WIM pour le pesage des trains, y compris l'interface du système qui emploie des graphiques de locomotives et de wagons.

Mots-clés: précision, B-WIM, erreur de mesure, train, pesage en marche.

1. Introduction

This paper discusses results obtained in a 2-year research project BridgeMon which was funded under the *Research for the Benefit of SMEs* scheme of the European Commission's 7th Framework Programme. The two main objectives of the project were to work on tools for bridge health monitoring and to enhance accuracy and performance of SiWIM® bridge weigh-in-motion system manufactured by a SME partner in the project, Cestel from Slovenia. This paper deals with the extensions of bridge weigh-in-motion (B-WIM) technology to railway bridges which was first researched around ten years ago, see (Liljencrantz, Karoumi, & Olofsson, 2005) and (James, 2005), but has never reached the implementation phase.

2. Bridge weigh-in-motion background

B-WIM systems use existing bridges as scales to weigh vehicles as they traverse the structure at full speeds (COST 323, 2002). A number of strain sensors are installed, typically around the mid-span section where responses due to the traffic loading are the highest (Žnidarič, Lavrič, Kalin, & Kulauzović, 2011). The most specific advantages of B-WIM systems over the pavement WIM systems are that the weighing platform (the bridge) is much longer than of any other technology, installations are completely portable and can be installed on the bottom side of bridges without interrupting the traffic (OBrien, Žnidarič, & Ojio, 2008).

The basic principle of a B-WIM algorithm (Moses, 1979) is to calculate the axle loads by minimising the difference between the measured response $g(t)$ and the theoretical fitted response $f(t) = A_1I(t-t_1) + A_2I(t-t_2) + \ldots$, where A_i is the ith axle load and t_i is the time of arrival of the ith axle at the coordinate system origin – the row of weighing sensors. The function $I(t)$ is known as the influence line (IL) and describes the response of the bridge at the sensor location to a passage of unit weight. The objective function depends linearly on the unknowns; the *singular value decomposition* (Press, Teukolsky, Vetterling, & Flannery, 2007) is used to find the axle loads.

2.1 Calculation of vehicle velocity and axle detection

Calculating the vehicle velocity requires two strain sensors which are mounted at different longitudinal locations on the bridge. Correlation between the two signals defines the time shift of one signal relative to the other at which the match between the signals is the best. The known distance between the two sensors and the time shift define the speed of the vehicle.

Modern B-WIM systems obtain axle information from strain signals captured under the bridge. As a result no bridge closure is needed during installation and maintenance. Reliable axle information requires strains sensors located where as sharp axle peaks as possible are detected. Optimal placement of axle detection sensors has been studied within the Bridgemon project (Corbaly, et al., 2014) but exceeds the scope of this paper.

Once the speed of the vehicle and the passage times of individual axles have been obtained, it is a simple matter to calculate the axle spacings by multiplying the speed of the train by the differences between the passage times of pairs of consecutive axles.

2.2 Influence Lines

Influence lines (IL) are the key structural parameters that define how bridge responds to traffic loading (OBrien, Žnidarič, & Ojio, 2008). Research and many years of experience have shown that the influence lines for B-WIM must be calculated from measurements (Žnidarič, Lavrič, & Kalin, 2002) as theoretical influence lines in most cases provide unrealistic description of actual bridge behaviour.

Unlike (OBrien, Quilligan, & Karoumi, 2006) who use vehicles of known axle loads and spacings and an inverse Moses algorithm to derive the experimental influence lines, the SiWIM® system uses a non-linear minimisation procedure and random vehicles, without knowing their axle loads and spacings. A few hundreds of such evaluations are averaged into the influence lines that are used for further calculations. ILs are modelled with cubic splines for which some of the points are fixed and locations of some are "forced" to specify the supports and peaks of the IL. Since the system no longer depends linearly on the unknowns, the calculation method is inherently non-linear. Powell's minimisation (Press, Teukolsky, Vetterling, & Flannery, 2007) is applied for solving the problem. More details about calculating influence lines are given in (Žnidarič, Kalin, & Kreslin, 2016).

3. Railway bridge weigh-in-motion system

3.1 Nieporęt Railway Bridge

The objective of BridgeMon project was to extend the established road applications of B-WIM system to railways. As this work was done primarily for the Polish SME Adaptronica, a typical Polish truss bridge was chosen for testing of the Rail B-WIM software. Located in Nieporęt, near Warsaw, it is among over one thousand similar bridges in Poland (Kolakowski, Sala, Pawlowski, Swiercz, & Sekula, 2011). Its steel truss is 8m high, spans over 40 m and consists of five 8 m long bays. Figure 1 shows an elevation (a) and a view from underneath the bridge (b).

The bridge is seriously deteriorated and damaged. As a result, velocity of the trains when crossing the bridge is limited to 20km/h. More details of the bridge can be found in (Cantero, Kreslin, & Corbally, 2013).

3.2 Field Testing

Field testing was performed between 20th and 25th of May, 2013. During this period 27 other passenger and 19 cargo trains were captured, including four trains that were weighed beforehand on the low-speed weigh-in-motion weighing station near Warsaw.

a) b)

Figure 1 – Nieporęt Bridge: side view (a) and view from underneath (b)

3.3 Sensor locations

Strain sensors were installed on the longitudinal trusses, on stringers and on cross beams. To avoid welding or drilling, steel mounting plates were applied as the interface. They were glued to the structure with epoxy and, after hardening, the strain sensors were fastened with nuts, as shown in Figure 2, left. In addition, a few extra strain gauges were glued directly on the steel structure.

One of the main characteristics of a B-WIM installation is that any intervention from the track side can be avoided, which is an important advantage from safety and maintenance points of view. Therefore, it was envisaged that the sensors on the beams, right beside the sleepers, would be used for axle detection. However, signals from the passing trains revealed that the axle loads distributed over the entire *rail-sleeper-bridge* system did not provide sharp peaks of individual axles in a bogie (double or triple axle). Thus the sensors were moved from their initial locations to the bottom flange of the rail between two sleepers (Figure 2, right). These sensors could have also been used for weighing, as with some existing railway WIM systems, yet this was not the purpose of the project.

Figure 2 – Strain sensors attached over glued mounting plates

3.4 Preliminary railway B-WIM results

The conventional B-WIM system used constantly monitors the measured strains. Then it forms the so-called *events* that store all activities that exceed predefined strain thresholds. In later stages, the software for each individual event calculates average speed of the event, defines axles, merges axles into vehicles, performs weighing and displays the results.

The fundamental difference that required adaptation of road B-WIM system for railways was length of the trains. As they come with indefinite combination of wagons, these cannot be all stored in classification tables as road vehicles are. Consequently, a new module was written that can deal with locomotives and individual wagons within a train.

After sensors were installed the system was setup by calculating the influence lines, sensor factors (Žnidarič, Turk, & Zupan, 2015), calibration factors etc. Figure 3 (see also the detail of first four vehicles in Figure 4) presents the response of a train. It can be seen that the calibrated system provided almost a perfect match between the measured (blue) and calculated (purple) strain responses.

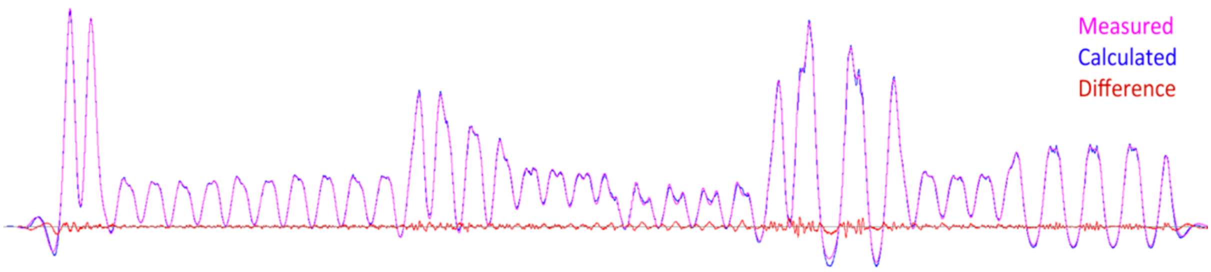

Figure 3 – Measured and calculated signals of train 1

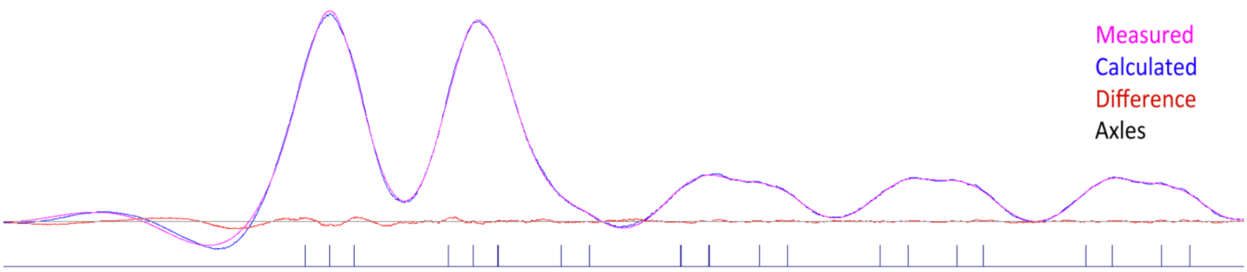

Figure 4 – Measured and calculated signals of train 1 – detail of locomotive and first three and a half wagons

This is an important but not the only condition for getting accurate results. It is however a guarantee that physical measurements were performed in the best possible way.

3.5 Low-speed weighing of trains

To verify the results of the measuring system, four cargo trains were weighed on a low-speed weigh-in-motion scale (Figure 5) in a railyard in Warsaw that operates at speeds of up to 5 km/h. All trains consisted of a 6-axle locomotive and 25 to 38 wagons of different length, axle configuration and loading. Due to the limitations of the low-speed device only gross weights of wagons, without individual axle loads, were collected and could have been compared with the B-WIM results.

Figure 5 – Low-speed weigh-in-motion system for train weighing (left) and one of the calibration trains on it

4. B-WIM results

All four trains were calibrated with the electric locomotives ET22 (Figure 6) which has six axles and standard and more or less constant gross weight of 6 × 20 = 120 tonnes.

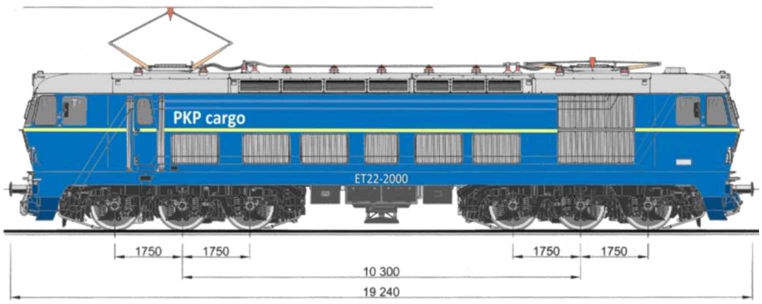

Figure 6 – ET22 Locomotive configuration (from www.locomotives.com.pl)

Figure 7 summarises the initial results for all four reference trains. The thicker solid lines present the gross weight error of B-WIM results for locomotives and individual wagons and the dashed lines velocities of individual wagons. The following apparent conclusions were made:

1. While the results of train 2 were extremely good, with the peak-to-peak error just slightly over 2% and the standard deviation of error only 0.56%, the errors of other three trains exceeded 30%.
2. The obvious reason for errors was the assumption of constant velocity of all vehicles in an event. On the road this proves to be acceptable for accurate weighing, even if the vehicles do not drive at the same speed, but trains are too long for such assumption.

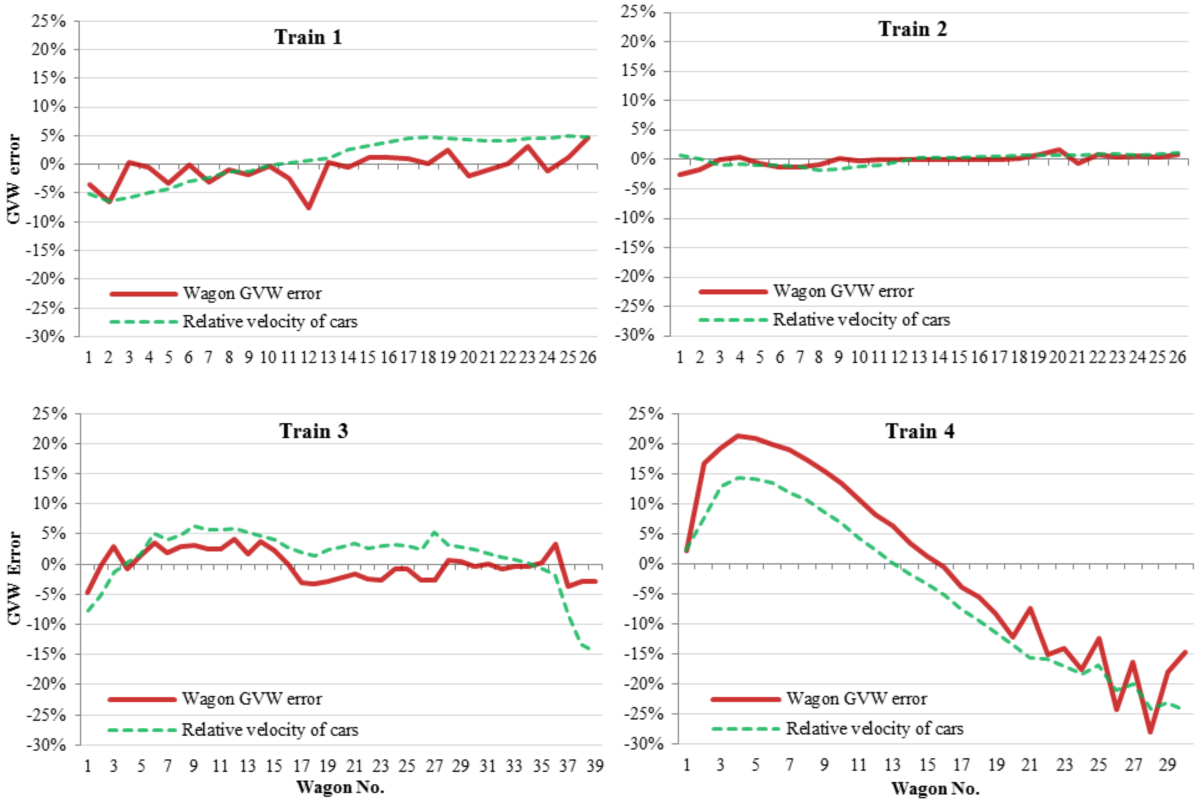

Figure 7 – Error in gross weights and variation of velocity of individual wagons – trains 1 to 4

4.1 Effect of non-constant velocity of trains

On Nieporęt Bridge the varying train velocity influenced enormously the results. The 20 km/h speed limit resulted in significant breaking and acceleration of the trains during their crossings of the bridge. This was exaggerated for longer trains, some of which exceeded 500 m in length. As the variation in measured speed in the worst case (train 4) surpassed 25%, the assumption of constant velocity clearly was not appropriate and had to be overcome.

4.2 The solution

The solution for this problem was to replace in the algorithm the constant velocity of the train with individual wagon velocities. In the standard processing chain, the velocity is calculated as the first step after splitting the signals into events. The per-lane velocities for the event, in this case the average velocity of the train, are calculated using cross-correlation of the entire signals from pairs of speed measurement points (SMPs). The next two steps are identification of axles and merging of axles into vehicles. Then the axle loads are evaluated and the raw results are multiplied with calibration factors to obtain the final results.

In the modified algorithm, an additional step has been inserted to calculate the per-carriage velocities using correlation of only those parts of the signals that contain information for the passage of a single locomotive or wagon.

The improvement in accuracy for the four reference trains was significant. Figure 8 displays the errors in the predicted wagon gross weights for each of the trains when considering (i) the average velocity of the train obtained from the entire loading event (solid lines) and (ii) varying velocities calculated for each of the wagons (dashed lines).

It shall be noted that the fourth reference train still exhibits large errors for the first four carriages. A heavy rain just before the crossing of this train and not sufficiently protected strain gauges (due to short test campaign) resulted in noisy speed measurement signal (the shaded area in Figure 9) and, consequently, erroneous velocities for these wagons. Such errors can easily be avoided by properly protecting the sensors against environmental effects.

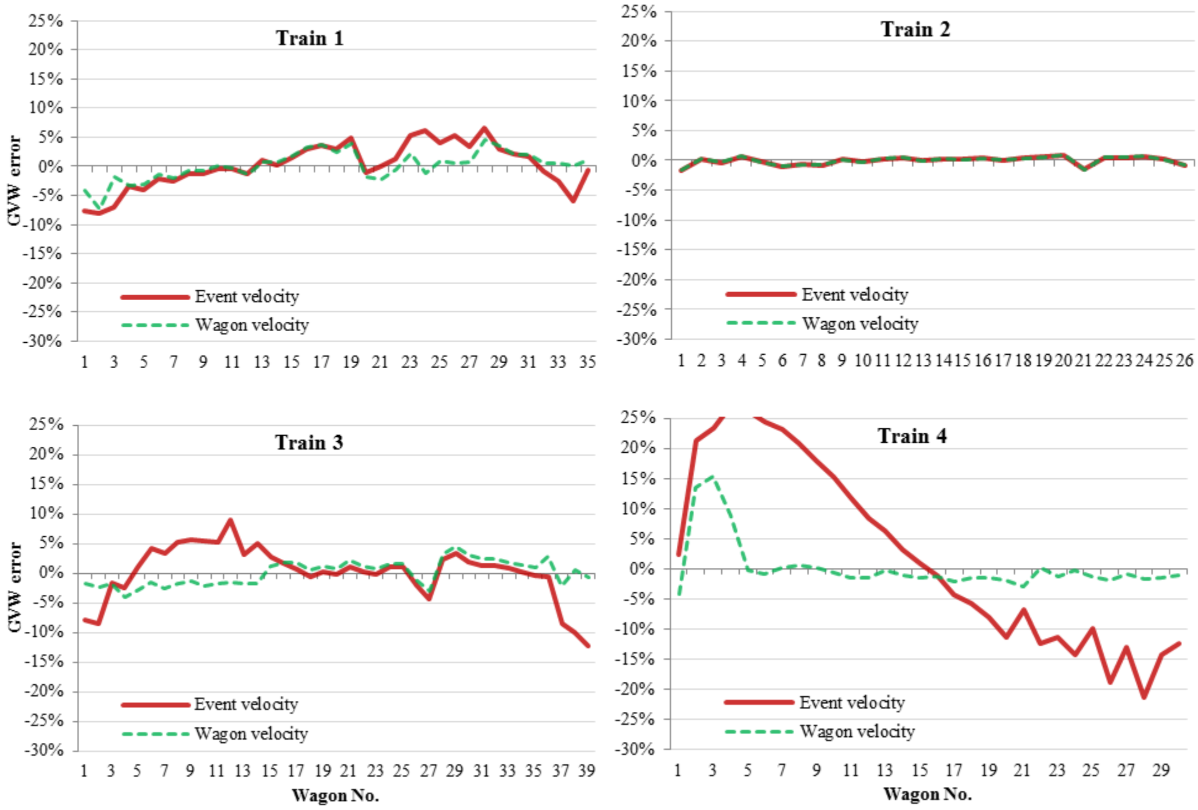

Figure 8 – Error in gross weights of velocity of individual wagons – trains 1 to 4

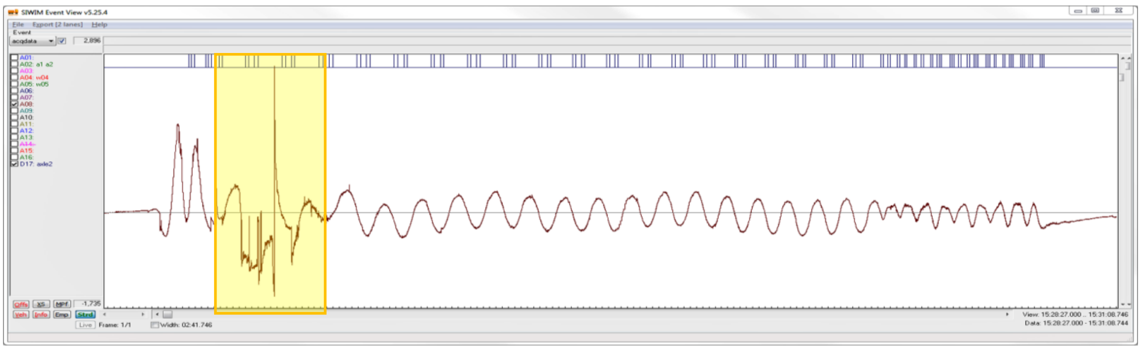

Figure 9 – Error in velocity detection sensor (shaded area)

4.3 Additional modifications

To further improve the velocity calculation, another modification to the algorithm has been implemented and partially tested. It is based on the fact that axle spacings for locomotives and wagons are well defined.

Once vehicles have been identified and their individual speeds calculated, the axle spacings were compared against specifications of known axle spacings provided by Polish Railways. The nearest match was found and if the differences of all axle spacings were within the predefined tolerances (0.2 m was selected), it was assumed that a standard locomotive or wagon was found and axle spacings from the specifications were applied. First, the speed was adjusted so that the total measured length of the vehicle matched the sum of all axle spacings from the specification. Then the axle spacings themselves were adjusted.

Simulations have shown further modest improvements of accuracy. One obstacle was that not all axle spacing configurations captured on site were included in the specification provided.

Finally, the interface was adapted for railways. A number of extra parameters had to be included to implement the features described above. These are stored in several additional configuration files. Then, a new classification table was setup that defines characteristics of locomotives and carriages that circulate on Polish railways. As a final point, the software interface was adjusted to display locomotives and wagons instead of heavy road vehicles.

5. Accuracy of railway B-WIM results

Table 1 summarises the results obtained with traditional road B-WIM system and those obtained with all railway-related improvements described in the paper. The columns display the mean values and standard deviations of errors of four reference trains obtained by conventional and modified B-WIM algorithms. Clearly, improvements were substantial and have potential for further advancements when requests by a particular railway operator are advised.

Table 1: Summary of results

Train	Original		Modified	
	Mean error	COV of errors	Mean error	COV of errors
1	3.0%	3.6%	2.3%	2.8%
2	0.5%	0.7%	0.5%	0.7%
3	3.3%	4.6%	1.2%	1.6%
4	13.3%	15.4%	2.2%	3.2%

6. Conclusions

Knowing the true loads of the trains is getting more and more important, in particular in relation to splitting the operation and infrastructure maintenance roles and to comply with the interoperability principle and the networks that shall be on disposal to various train operators.

The EC 7^{th} Framework Programme research project BridgeMon investigated two issues related to railway bridges: adaptation of B-WIM system to railway bridges to collect accurate in-motion traffic loading information and structural health monitoring (SHM) system. It was suggested that a combined B-WIM and SHM system would be a very useful tool for bridge owners that would help them keeping the aging bridge stock at an acceptable level of reliability. A railway bridge in Nieporęt in Poland was selected for testing the B-WIM and SHM concepts.

For the railway B-WIM part of the research, a typical Polish railway bridge was instrumented with strain transducers, strain gauges and other commercial bridge WIM hardware. This was until before this project applied exclusively on road bridges and had to be modified for weighing of the trains.

During a 3-day testing period forty-six trains were captured. Four of them have beforehand passed a low-speed WIM station in Warsaw and, knowing the actual weight of each wagon, allowed testing of accuracy of the B-WIM system.

Initial results demonstrated that one of the four trains of known weight, the only train which crossed the bridge with constant speed, was weighed very accurately, with all wagon weights errors falling within the -0.9% to 1.6% error interval. This suggests that accuracy potentials are much higher than it could have been shown on the Nieporęt Bridge. However, accuracy of the other trains was disappointing with calculated wagon weights deviating by as much as 30% from their reference values. An in-depth analysis revealed that these trains were changing speed as they traversed the bridge and that the large errors were directly correlated to it. The standard B-WIM algorithm, which assumed a constant velocity during the passage of a vehicle, was adapted accordingly. Results improved significantly, with 75% of all calculated wagon weights falling within ±2% and 97% of them falling within ±5% of their actual values. These values include the 4 wagons which due to the rain had an issue with accuracy. Further developments tailored the B-WIM algorithm for weighing trains, including the system interface that employs graphics of locomotives and wagons.

The development of railway B-WIM has shown its potential for railway applications. The remaining challenges include a) finding better ways for axle detection on the main bridge members that would remove sensors on the track side, which is the key B-WIM advantage from safety and maintenance points of view, b) better integration of known vehicle parameters, i.e. having a complete list of locomotive weights and wagon axle spacings and c) testing of the system on other types of bridges; a steel truss is a common but complex structure to apply B-WIM on. Some solutions have already been investigated and proposed in the Bridgemon project reports (Ni Choine, Žnidarič, Corbally, & Kalin, 2014). Last but not least, combination of results obtained from the rail and from the bridge may further increase accuracy of railway WIM system results in general.

7. Acknowledgment

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WEIGHING VEHICLES IN-MOTION IN THE HIGHWAY AND RAILWAY MODES: COMPARATIVE ANALYSIS AND LESSONS LEARNED

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Abstract
This paper conducts a comparative analysis of weigh-in-motion (WIM) systems and wheel impact load detectors (WILD) in an effort to identify potential opportunities to enhance practices involving vehicle loading data. Similarities were found between the two technologies in terms of available data and methods to assess data accuracy. While data from highway WIM systems are currently used as infrastructure design inputs, WILD systems have historically been used to identify severe impact loads known to damage railcars and track. The results of an illustrative analysis reveal the value of enhancing the level of detail currently available in data from highway WIM systems and broadening the types of applications of WILD data. Specifically, there is a need to explore more robust applications of load spectra for data-driven track design.

Keywords: Weigh-in-Motion (WIM), Wheel Impact Load Detector (WILD), Data Accuracy, Infrastructure Design, Load Data Applications, Data Usage Practices

Résumé
Ce document montre une analyse comparative des systèmes de pesage en marche (WIM) et des détecteurs d’impacts de roues (DDR) dans le but d'identifier les opportunités potentielles pour améliorer les pratiques de chargement du véhicule. Des similitudes ont été trouvées entre les deux technologies en termes de données disponibles et de méthodes pour évaluer la précision des données disponibles. Bien que les données provenant des systèmes WIM routiers soient actuellement utilisés comme entrées de conception de l'infrastructure, les systèmes DDR ont historiquement été utilisés pour identifier les charges d'impact importantes qui sont connues pour endommager les wagons et les rails. Les résultats d'une analyse illustrative révèlent l’importance de l'amélioration du niveau de précision des données des systèmes routiers WIM et l’élargissement des types d'applications de données DDR. Plus précisément, il est nécessaire d'explorer des applications plus robustes des spectres de charge pour la conception des données de la piste.

Mots-clés: Pesage en marche (WIM), détecteur d’impacts de roues (DDR), précision des données, conception des infrastructures, applications de données de charge, pratique de l’utilisation des données de pesage.

1. Introduction

Both the highway and railway modes utilize technology systems to measure loads imposed on infrastructure by vehicles while they are in-motion. Highway weigh-in-motion (WIM) systems provide information on axle loads, axle configurations, and vehicle speeds. Wheel impact load detectors (WILDs), which are a predominant type of equipment used for in-motion measurements on railroads, are capable of providing similar information. As implied in their name, however, the primary use of WILD systems is to detect high impact wheel loads. Although the type and extent of data applications differ for WIM and WILD systems, information from both can be used for, *inter alia*, infrastructure design, maintenance programming, and enforcement. In particular, data collected by WIM systems is increasingly used for infrastructure design applications. For WILD systems, infrastructure design approaches incorporating impact loading data are not mainstream; however, such approaches may hold promise in the future.

This paper identifies similarities and differences between WIM and WILD systems through a comparison of equipment characteristics, current application practices, and data accuracy. This is accomplished through a review of relevant literature and industry practice. Although this paper primarily focuses on single strip WIM sensors, it is important to note that other sensor types exist such as multiple strip and bridge WIM (BWIM). An illustrative analysis of sample data reveals opportunities to enhance the value of WIM and WILD data through more detailed data capture and broader application of the data. While the analysis is illustrative, the results support relevant insights for practitioners involved with WIM and WILD systems.

2. Comparison of Equipment Characteristics

2.1 WIM Characteristics

Six predominant WIM systems are used throughout the world. Piezo-polymer WIM systems consist of a sensor embedded in the pavement, which produces an electric charge from which the applied load can be determined. Piezo-quartz WIM systems feature quartz disks that are installed under a sensor, which yield an electric charge proportional to the axle load. Bending plate WIM systems comprise two steel platforms fitted with strain gauges which are used to determine the axle loads. Load cell WIM systems comprise hydraulic load cells installed beneath platforms to measure axle loads (FHWA, 2015). Capacitive strips consist of two or more electrically charged metal plates, with the capacitance of the system changing proportionally to the applied loads. Finally, BWIM systems measure strains on the soffit of a bridge and use these strains to determine the applied vehicle load (O’Brien et al., 2011).

2.2 WILD Characteristics

WILD systems typically consist of a series of strain gauge load circuits welded onto the neutral axis of a rail (Stratman et al., 2007), referred to as the instrumented zone. This is where wheel load measurements take place. The strain gauges use a relationship between load and deflection to determine the magnitude of loads applied. Signal processors are situated near the instrumented zone, which electronically monitor and store data (Stratman et al., 2007). WILD sites are typically constructed on high quality, tangent (straight) track, with concrete crossties, premium ballast, and well-compacted subgrade.

Throughout the instrumented zone, there are typically 16 measurement points along each rail, each using four strain gauges (two each for vertical and lateral load measurements). Therefore, a typical WILD setup will include 64 strain gauges per rail, totaling 128 (Stratman et al., 2007). In this paper, a vertical load taken at a single measurement point is referred to as a raw load. These raw loads are point loads, rather than loads developed from an average of a road contact area, in the case of certain WIM systems. Figure 1 shows a typical WILD configuration. Data measured by WILD systems includes: location, time, rail, speed, axle configuration, type of rolling stock, and 16 vertical and lateral load measurements per wheel.

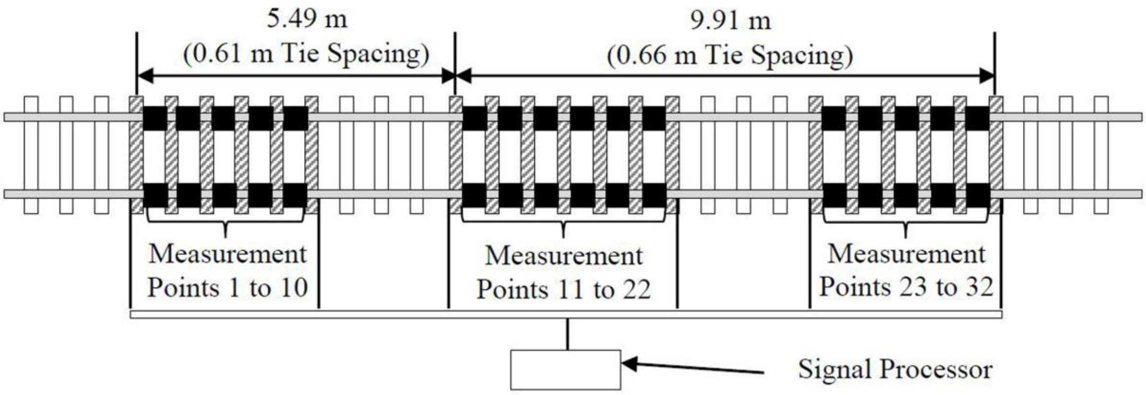

Figure 1– Schematic diagram of WILD equipment installation

3. Comparison of Current Application Practices

3.1 Current Practices with WIM

In North America, pavement design is a primary application of WIM data. This involves estimating the axle loads expected to be imposed on a pavement structure throughout its design life. With the aid of computer software, these axle loads are used to evaluate the performance of a pavement structure during the design phase (AASHTO, 2008). Truck weight enforcement is another application of WIM data in North America. Current practice involves the use of WIM equipment as a pre-screening tool, with truck weight violations confirmed using a static weigh scale. Direct enforcement using high-speed WIM systems is not currently implemented in North America (FHWA, 2015).

3.2 Current Practices with WILD

WILD systems are commonly used for structural health monitoring of railcar wheels (Stratman et al., 2007). Railroads use them to identify and remove wheels with flat spots on the tread which cause high impact loads on the rail, wheels, and bearings. Van Dyk (2014) categorizes the types of loads imposed on the track structure as follows:

- Static loads reflect the weight of the axle at rest.
- Dynamic loads reflect the dynamic effects due to wheel-rail interaction. These loads are superimposed on the static load.
- Impact loads are a type of dynamic load and represent the highest loads imposed on the track structure. These are usually a result of wheel and track irregularities, and cause substantial damage to the rail infrastructure. Impact loads occur when total loading (i.e., sum of static and dynamic loads) exceeds 40,823 kg (90,000 lb) (Stratman et al., 2007).

A WILD implementation captures raw loads (i.e., it measures the loads imposed by a single rolling wheel multiple times). A common practice is to take the average of all raw loads for a single wheel as it rolls through the instrumented zone (Van Dyk, 2014). This is referred to as the nominal load and is considered an estimation of the wheel's static load, analogous to a load captured by a conventional WIM.

4. Comparative Assessment of Data Accuracy

4.1 Accuracy of WIM Data

Two different types of inaccuracies exist with WIM equipment: random and systematic (Prozzi et al., 2008; Davies and Sommerville, 1987). Random inaccuracy reflects measurement fluctuations due to the inability of the sensor to capture the weight precisely, while systematic inaccuracy generally persists in one direction (Prozzi et al., 2008). Many variables contribute to inaccuracy, including sensor type, smoothness and geometry of the road surface, environmental factors, and vehicle factors (Farkhideh et al., 2012). These variables also contribute to the dynamic nature of vehicle loads, causing the true loads to oscillate above and below the static load (Papagiannakis et al., 2008).

Standard accuracy analysis involves comparing weights measured at WIM sites to the weights of the same vehicles measured at certified static weigh scales. Results are then compared to set standards, an example of which is set out by the American Society of Testing and Materials (ASTM) (ASTM, 2009), as shown in Table 1. To illustrate, this table presents the results of three Canadian studies (Zhi et al., 1999; Farkideh et al., 2012; Wood et al., 2016) which tested WIM accuracy in this manner. In Table 1, tolerances are calculated as follows:

$$Tolerance = 100 * \frac{(W - S)}{S} \qquad (1)$$

Where: S is the static weight and W is the weight recorded by the WIM.

Table 1 – Certified weights versus measured weights at WIM sites

Function	ASTM Specified Tolerance	Recommended Confidence Level (ASTM)	Farkhideh et al. Confidence Level	Zhi et al. Confidence Level	Wood et al. Confidence Level
Steering Axle Load	±20%	95%	76-80%	70%	~100%
Axle-Group Load	±15%	95%	71-82%	≤50%	93-100%
Gross Vehicle Weight	±10%	95%	55-66%	<50%	87%
Equipment Sensor Type	-----	-----	Piezo-polymer	Piezo-polymer	Piezo-quartz

Table 1 indicates that ASTM requirements were not completely met for either of the studies involving piezo-polymer sensors. ASTM requirements were met part of the time for the study involving piezo-quartz sensors. Based on theoretical and field performance of WIM devices, accuracy remains an issue that must be addressed for all applications.

4.2 Accuracy of WILD Data

Like WIM data, WILD data are also subject to random and systematic inaccuracies. Although WILD systems are setup on high quality track to limit structural influences on measured load variations, there are still factors which may prevent accurate representation of the true loading environment. According to Hay (1982), a large contributor to load measurement variation is the dynamic nature of railcar loads, which are subject to roll, slip, lurch, shock, buff, torque, load transfer, and vibration. Figure 2 depicts the dynamic nature of railcar loads.

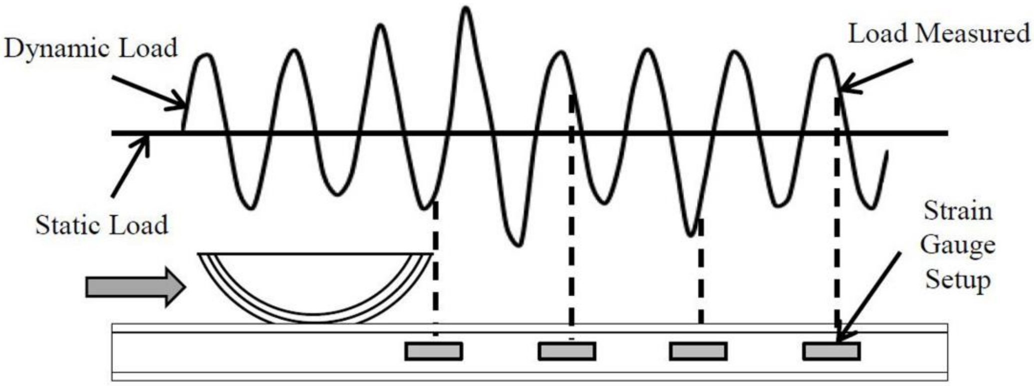

Figure 2– Schematic diagram of dynamic nature of railcar loads

Accuracy analysis for WILD equipment is similar to that of WIM equipment. Railcar gross weights measured at a WILD site are paired with their corresponding billed weights, taken at a certified static scale. Results are compared to set standards, an example of which is set out by the International Organization of Legal Metrology (OIML) (OIML, 2011). To illustrate, sample data sets from a North American Class I railroad, representing railcar weights from three in-service WILD sites, were used to assess accuracy relative to billed weights. After data validation, these comparisons were assessed against OIML standards. Results are shown in Table 2. In this analysis, tolerance is calculated using Equation 1 above.

Table 2 – Certified weights versus measured weights at WILD sites

Site	OIML Tolerance	OIML Recommended Confidence Level	Sample Size (paired railcar gross weights)	Confidence Level
Site 1	±2%	90%	7,878	84%
Site 2	±2%	90%	20,545	59%
Site 3	±2%	90%	8,193	65%

Table 2 indicates that OIML requirements were not satisfied. Notably, the OIML tolerances are more stringent than those specified by ASTM for highway WIM systems, since WILD sites are often used for applications such as overweight citations. This finding is only relevant for a small sample of WILD data and is not intended to be representative of all WILD equipment. It is presented here to illustrate that the accuracy assessment method used for WILD data is similar to the method used for WIM data.

The repeatability of WILD measurements at different car positions within a train is also an important consideration. An analysis was completed using sample data from 18 trains in 2006, recorded at an in-service WILD site located in the United States Midwest. In this analysis, railcar weights were again compared to certified billed weights, and percent differences were calculated. The results, shown in Table 3 as an average of all 18 trains, reveal that percent differences were the most consistent for the final 3/4 of the train. These results are only illustrative, but suggest that the precision of WILD measurements changes with car position.

Table 3 – Precision of weights measured at WILD sites as a function of car position

Standard Deviation in Percent Differences of Weights (%)			
First Quarter	Second Quarter	Third Quarter	Fourth Quarter
0.49	0.38	0.32	0.35

5. Illustrative Analysis

This section illustrates potential opportunities to enhance the value of WIM and WILD data through more detailed data capture and broader application of the data. It describes the analytical framework, source data, results, and the implications and limitations of the results.

5.1 Analytical Framework

Based on the current capabilities and application of WIM and WILD data, the analytical framework applied in this paper has been designed to answer two main questions:

1. What can highway WIM manufacturers, suppliers, and users (the highway WIM community) learn from the structure and detail available in datasets generated by WILD equipment?
2. What can WILD manufactures, suppliers, and users (the WILD community) learn about potential utilization of WILD data from practices within the WIM community?

The first question, which is the primary focus of this paper because of its relevance to the highway WIM community, is addressed by analyzing a WILD data sample. The following subsections describe the approach and results of this analysis and reveal implications regarding the trend to enhance the level of detail available from highway WIM equipment.

The second question, which is more relevant to the WILD community, is addressed by demonstrating the potential utility of the entire WILD dataset, not just the high impact loads. Specifically, for this illustrative analysis, the sample WILD data are used to develop load distributions (or spectra) in a manner analogous to the development of axle load spectra (ALS)—a key input to the mechanistic-empirical pavement design process. The broad implication here is that if WILD data were compiled into load spectra, there may be opportunities for railways to use these data to inform more effective track design.

Prior to developing ALS from WIM measurements, the axle load data is disaggregated by time, vehicle class, and axle group (i.e., single, tandem, tridem, quad). WILD systems measure dynamic vertical loads similarly to WIM systems, and loading data can be disaggregated by time period, railcar type, and railcar axle group (truck). The key difference is that WILD systems typically make 16 vertical load measurements for each wheel (i.e., raw loads) rather than the single representative axle load measurement produced by conventional WIM systems. This allows further disaggregation of WILD data by wheel. However, load spectra can be developed from the detailed raw loads, from nominal vertical wheel loads, or from axle loads.

5.2 Source Data

The illustrative analysis uses a sample of WILD data collected from February 10, 2016 to February 11, 2016 at two different sites located in the United States Midwest. The sites share similar characteristics: standard rail gauge, tangent (straight) track, negligible grade, newer rail, and a typical track substructure. Before analysis the data was validated to remove anomalies. The following steps were taken:

- For some trains, anonymous false axles were detected and removed.
- Vertical loads less than 3,175 kg (7 kips) (representing the tare weight of a typical rail car) were deleted. Tare weight was taken as 3,742 kg (8.25 kips) per wheel with 567 kg (1.25 kips) of tolerance.
- No load exceeded 42,547 kg for the trains selected (no erroneous high loads).

In total, 10 trains were selected for analysis from Site 1 while 7 trains were selected for analysis from Site 2.

5.3 Analysis Results

Three illustrative analyses were conducted to better understand the structure and detail available in a WILD data set: (1) raw load variations; (2) differences between the load spectra developed from raw loads and nominal wheel loads; and (3) a comparison of loads imposed on the two rails (north rail, south rail) at a specific site.

5.3.1 Raw Load Variations

This analysis characterized the variations in measured loads experienced by a single wheel from one measurement point to the next. For each wheel in the dataset, each of the 16 raw load measurements (barring equipment malfunction) were compared to that wheel's nominal load and the differences were calculated (as percentages). These variations (percent differences) were compiled into distributions, as illustrated in Figure 3. There were 109,164 such variances calculated in making these distributions for the north rail.

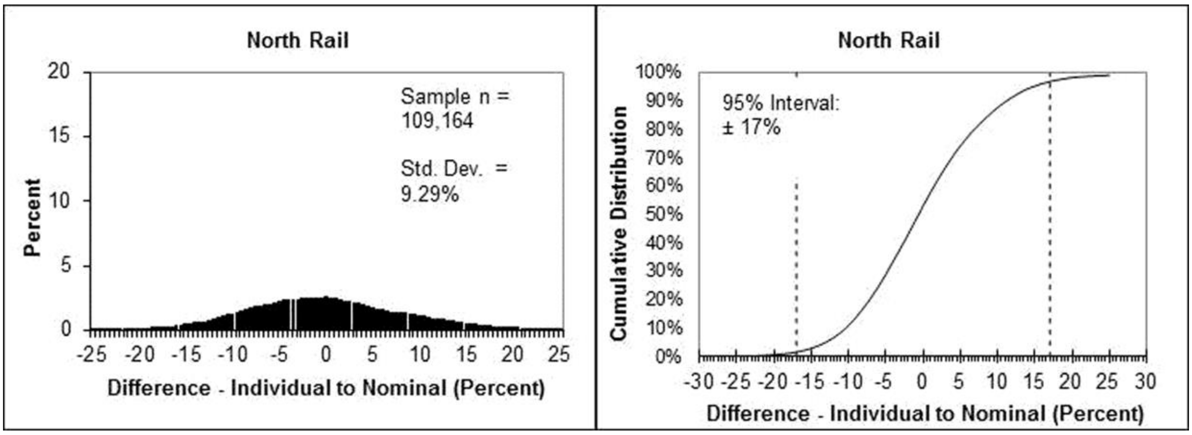

Figure 3 – Frequency and cumulative distributions of raw load variations

As seen in Figure 3, for the north rail, the standard deviation of the variations is 9.29 percent, with 95 percent of all variations being within ±17 percent. The south rail yielded similar results, with a standard deviation of 9.63 percent and 95 percent of all variations being within ±18 percent. In this case, the nominal wheel load is considered the *closest* representation of the true wheel load. This analysis shows that the difference between a raw load and the nominal wheel load can reasonably reach 18 percent.

5.3.2 Load Spectra Developed from Raw Loads and Nominal Wheel Loads

This analysis determined the differences between compiling load spectra using raw loads and compiling load spectra using only nominal wheel loads. For each method, load spectra were developed using all axles for the 17 selected trains, with key statistics reported. Figure 4 illustrates the differences between the load spectra for the two methods. For the north rail, sample sizes of 109,164 raw loads and 7,028 nominal loads were used in the distributions.

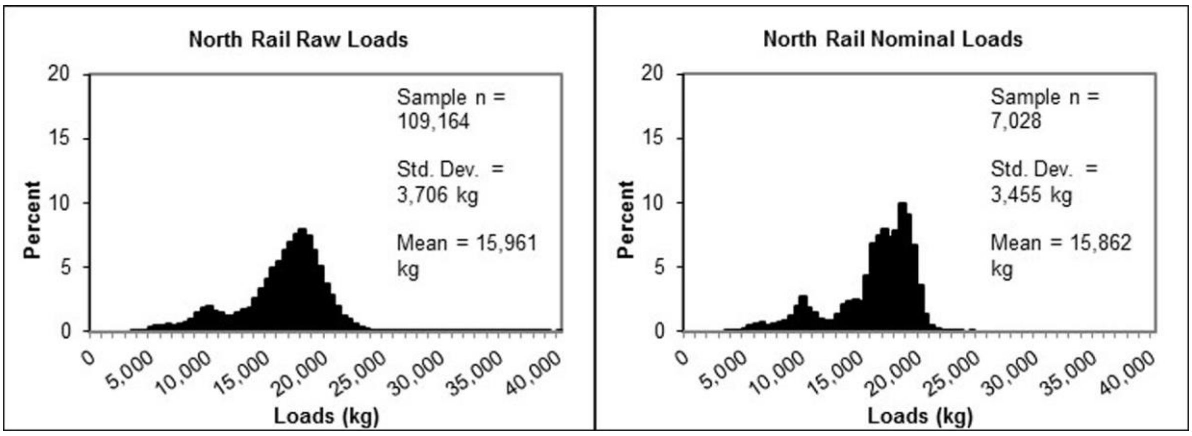

Figure 4 – Load spectra developed from raw loads and nominal wheel loads

As shown in Figure 4, the load spectra developed using nominal wheel loads (at right) has a standard deviation of 3,455 kg rather than 3,706 kg, indicating that there is less spread in the data. Nominal loads are computed by taking the average of all raw loads for a given wheel. Due to this procedure, it is expected that nominal loads are less likely to be very high or very low. The mean loads are not identical only in the cases where nominal loads were computed with one or more raw loads not being recorded due to equipment malfunction (e.g., a weighting factor of 1/15, rather than 1/16). Results for the south rail were similar.

5.3.3 North Rail versus South Rail

This analysis reveals differences in nominal wheel loads imposed on the two rails at a site. Load spectra were developed using all axles recorded at each site. Figure 5 illustrates the north rail and south rail load spectra at Site 1. Sample sizes of 4,542 nominal loads were used for the north and south rail distributions, respectively.

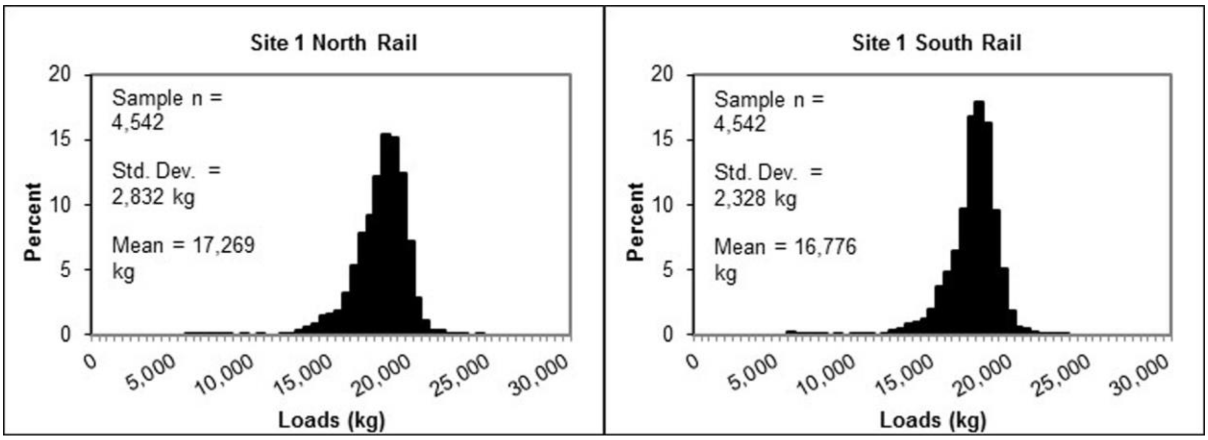

Figure 5 – Load spectra from nominal wheel loads for the north and south rails

Figure 5 reveals differences in the means and shapes of the two distributions. Furthermore, an independent samples t-test conducted between the two distributions suggested that they are statistically different, with a p-value of 0.001. This shows that for sites with straight track and negligible grade, loading conditions still may differ from rail-to-rail.

5.4 Lessons Learned and Limitations

The foregoing analysis reveals insights for both the WIM and WILD communities. For the highway WIM community, the findings illustrate three key points. First, as expected, there is variability in a single wheel’s load as it rolls along a track. The ability to measure this variability offers a truer reflection of the loads actually imposed on the track. While it is recognized that this variability also occurs for a truck wheel as it rolls along the road, some currently-installed WIM systems do not report wheel loads or the variation within a single wheel’s load. The second point, is that characteristics of load spectra depend on whether raw loads or nominal wheel loads are used to compile the spectra. By extension, there is presumably also a difference between spectra developed from point loads and those developed from representative axle loads (as is the practice for pavement design). The underlying design issue is to balance how well load spectra represent the actual loads imposed on the infrastructure with the feasibility of collecting the data necessary to compile the spectra. Third, there is a need to better represent side-to-side variations in wheel loads. This capability, which is available for WILD systems, is now emerging within highway WIM systems. Current highway infrastructure design practices are not well-suited to account for this side-to-side variability, if such variability is deemed influential on ultimate performance.

For the WILD community, the analysis illustratively demonstrates the potential utility of the WILD data to support data-driven track design processes. More extensive analysis of load spectra developed from WILD data will help identify temporal and spatial loading patterns as well as industry- or track-specific loading characteristics. As with highway infrastructure design, there is potential to use these load distributions as a fundamental design input. This requires a thorough understanding of the interaction of loads and track components.

The illustrative nature of the analysis presented in this paper is the main limitation. While the analysis provides useful insights, further analysis using a much larger WILD data set are necessary. There is also a need for further research to evaluate emerging capabilities within the WIM community to provide more detailed load measurements (e.g., wheel loads). Finally, the findings should not be viewed as an endorsement of mechanistic design approaches. While these approaches hold promise, they involve complex data collection and design processes.

6. Conclusions

Both the highway and railway modes have substantial experience with the in-motion weighing of vehicles. While similarities exist, the impetus for developing in-motion weighing technologies in these modes differs, as does the current utilization of the data produced by these systems. This paper reviewed the characteristics of WIM and WILD systems, briefly described current deployment practices, and outlined standard methods for assessing system accuracy. An illustrative comparative analysis revealed the following insights about potential opportunities to enhance the value of WIM and WILD data:

- WIM and WILD systems both record comprehensive measurements about characteristics of in-motion vehicles. Compared to some highway WIM systems, WILD systems report more detailed data such as multiple loads per wheel (raw loads) and lateral loads.

- WILD systems have historically been used for structural health monitoring purposes. The current use of highway WIM data for infrastructure design—particularly the compilation of axle load spectra—suggests a similar potential application for WILD data.
- Relative to highway WIM systems, the accuracy of WILD systems is assessed using more stringent standards.
- WILD systems are designed to measure a known damage mechanism (i.e., impact loads). Similarly, emerging highway WIM systems are being developed to measure wheel-pavement stress distributions to better represent pavement damage.
- Finally, a more mechanistic understanding of loading and load transfer into the track substructure can inform more innovative track design methods. Such methods are gradually being applied to support pavement design, though they are complex (and costly). Nevertheless, there is potential for data-driven design to result in safer and more cost-effective infrastructure which is better-suited for actual in-service loads.

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Session 9 : Bridge WIM

Chair: Ales Znidaric (ZAG, Slovenia)

RECENT ADVANCES IN BRIDGE WIM TECHNOLOGY




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Abstract

WIM systems are typically divided into two families of technologies, the pavement and the bridge ones. They both provide equivalent information about heavy duty vehicles crossing the system: exact time stamp, gross weight, axle loads and spacings, vehicle velocity, its category etc. While the pavement systems use strip or plate sensors embedded into the pavement, the bridge weigh-in-motion (B-WIM) ones apply sensors attached to the superstructure of existing bridges or culverts. This paper describes advancements in accuracy and long-term stability of the B-WIM system that were achieved within a 2-year research project financed by the European Commission. Features that resulted in two to four accuracy class improvements according to European WIM specifications are novel axle detection method, better calculation of experimental influence lines, consideration of measurement errors as well as correction of temperature and velocity effects. A new data quality assurance procedure also added value to the results of B-WIM measurements.

Keywords: accuracy, B-WIM, data quality, measurement error, weigh-in-motion

Résumé

Les systèmes de pesage en marche sont généralement divisés en deux familles de technologies, qui sont installées dans les chaussées ou sur les ponts. Ils fournissent des informations équivalentes sur les véhicules lourds qui traversent le système : horodatage exact, poids brut, les charges par essieu et espacements des essieux, la vitesse du véhicule, sa catégorie, etc. Bien que les systèmes en chaussée utilisent des bandes ou des plaques de capteur encastrés dans la chaussée, le système de pesage par pont instrumenté (B-WIM) applique des capteurs fixés à la superstructure des ponts ou ponceaux existants. Ce document décrit les progrès dans la précision et la stabilité à long terme du système qui ont été réalisés dans un projet de recherche de 2 ans financé par la Commission européenne. Les caractéristiques qui ont abouti à une amélioration de 2 à 4 classes de précision selon les spécifications du WIM européennes sont une nouvelle méthode de détection de l'essieu, un meilleur calcul des lignes d'influence expérimentales, l'examen des erreurs de mesure, et la correction des effets de la température et de vitesse. Une nouvelle procédure d'assurance de la qualité des données a également amélioré les résultats des mesures B-WIM.

Mots-clés : précision, B-WIM, la qualité des données, erreur de mesure, pesage en marche.

1. Introduction

Bridge-WIM or *B-WIM* refers to a specific method that uses an instrumented bridge or culvert to weigh-in-motion the passing vehicles. Since its appearance 35 years ago (Moses, 1979) it has undergone considerable improvements. After being researched in the late 1990s (WAVE, 2001), it entered the market in 2002 and nowadays provides results equivalent to the pavement WIM systems: axle loads, gross weight, axle spacing, velocity, vehicle category etc. (OBrien, Žnidarič, & Ojio, 2008).

The main advantages of B-WIM systems are:
- high accuracy on smooth and even reasonable accuracy on less smooth road surfaces,
- complete portability, without affecting accuracy,
- ease of installation, without the need to close the traffic, and
- they provide structural information for advanced bridge assessment (Žnidarič & Lavrič, 2010).

The disadvantages are that a suitable bridge is needed and that setting-up a system on less common structures requires substantial knowledge about bridge behaviour. More information and general principles of B-WIM technology can be obtained, for example, in (Žnidarič, Lavrič, & Kalin, 2010).

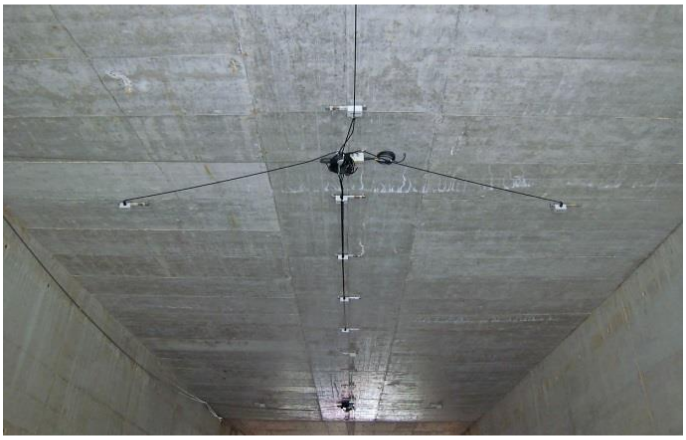

Figure 1 – Typical bridge WIM instrumentation

The commercial version of B-WIM, known as SiWIM®, is available for 15 years and has been used in over 20 countries around the world, primarily for short-term measurements lasting to up to one month. To extend its use to long-term measurements, to further improve accuracy of the results and to be able to instrument new types of bridges, a research project BridgeMon was proposed. It ran from 2012 to 2014 and was financed by the European Commission's 7th Framework Programme, from the fund supporting the small and medium size enterprises (SMEs). Its main objective was to support activities of four SMEs by developing tools for facilitating their market expansion (Žnidarič, Gavrič, Corbaly, & Hajializadeh, 2015).

Roughly half of the project was dedicated to B-WIM, including:
- improvement of data collection, involving more effective axle detection and strain measurements,
- consideration of effects caused by temperature, varying vehicle velocity and pavement roughness, and
- data quality.

This paper presents the main successful achievements of the project that have already been implemented in the SiWIM® system.

2. Bridges used to test B-WIM improvements

Three bridges in Slovenia were used to test various improvements and modifications of the system:

- The VA0468 Bridge is a typical medium-span beam-and-slab bridge appropriate for B-WIM measurements. It was constructed in 1997 as a single simply-supported span of 24.8m. The superstructure in each direction of traffic is made of five 1.4m deep prefabricated pre-stressed concrete beams and a 240mm thick cast-in-place deck on top. Beams rest on reinforced neoprene bearings at both ends of the bridge. This bridge was primarily used to test new ways of installing sensors for axle detection.
- The VA0028 Bridge is a 6-m span integral reinforced concrete slab structure, the most common type of a bridge used for B-WIM installations. It is permanently equipped with a B-WIM system and was as such used for testing of improvements related to long-term behaviour of the system.
- The VA0030 Bridge crosses the Sava River on the same A2 motorway, just 500m south from the VA0028. It was selected to compare accuracies of results on two different types of bridges, while taking benefit of the same statically weighed reference vehicles. The bridge is made of seven simply supported spans, one of which was instrumented. Each span consists of five 1.6m deep and 20m long pre-stressed beams that lie on reinforced neoprene bearings at both ends of the spans. They are covered with a 240mm thick continuous cast-in-place deck.

3. Improved Axle Detection Methods

One of the key advantages of B-WIM systems is that they can detect axles without putting any sensor on the road surface. This approach is known as FAD (Free-of-Axle Detection). Since its introduction in the WAVE project (2001) and installations on slab and beam-and-slab bridges, sensors were installed on the bottom flange of the beams or slab to measure strains for weighing. Additional sensors on the slab provided the necessary information for detection of axles (Žnidarič, Lavrič, & Kalin, 2010). Such setup is efficient on slab bridges and other flexible structures. However, on beam-and-slab bridges, many vehicles cross the bridge with their wheels directly over the beams. Then axles cannot be identified from the sensors on the slab, a shortcoming that had to be overcome.

3.1 Numerical modelling

Before starting the experimental work, a detailed 3-D numerical model was developed. Its purpose was to identify the best location to capture localized peaks due to the passing axles which are needed for efficient axle detection. AceFEM (2009) package built around Mathematica software (Wolfram, 2013) was used. The mathematical model of the whole structure, composed of around 40 000 standard 3D solid Lagrange 27-node elements is described in detail in (Cantero, Kreslin, & Corbally, 2013).

3.2 Model validation

A number of alternative axle detection measuring strategies have been simulated. Based on the results of modelling, the VA0468 Bridge was instrumented with seven strain measuring devices. Then, analytical results were compared with the results of measurements. Results of modelling and measurements are given in Figure 2.

Both results demonstrated that having sensors at the top of the beam web give sharp peaks that provide reliable axle information.

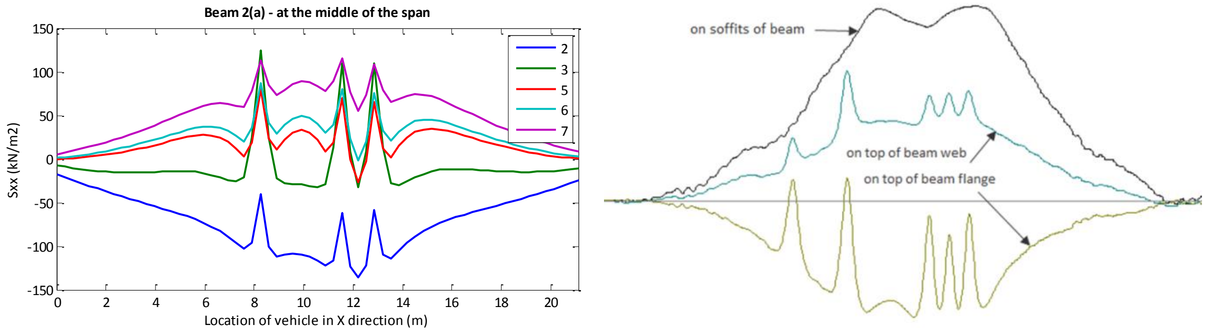

Figure 2 – Modelled response of a 3-axle vehicle at some locations (left) and measured response of a 5-axle vehicle (right)

3.3 Improvement of axle detection algorithms

The challenge for obtaining accurate information about vehicle axles with FAD setup lies in determining the optimum parameters within the various steps of the axle-detection algorithm. Time positions of axles are acquired from signals that are noisy and contain other information but axle peaks, like dynamic oscillations. On longer spans length of the influence line is also long compared to the axle spacings, making it difficult to distinguish individual axles in an axle group.

The pre-BridgeMon FAD algorithm used centred moving averages to circumvent these problems. The signal was averaged over a short and over a longer length and the two averages were subtracted. The difference was generally positive only in the regions of the axles, which allowed extracting axle information. However, on some bridges other influences make axle detection difficult. These include: low signal to noise ratio, interference with global effects, varying lateral position of vehicles and natural frequencies of the bridge that coincide with frequency of the axles.

To deal with these cases BridgeMon project worked on a number of enhancements:

- *improved signal processing for axle detection*: triangular window in moving average, Savitzky-Golay smoothing, two-phase thresholds, etc.
- *axle reconstruction*: the potentially missing axles are added and a second weighing is performed; if the fit of calculated strain signal with the measured signal is better by some predefined amount the reconstructed axles are retained,
- *combining several axle-detection channels*, to amplify peaks, either in lateral or longitudinal directions, etc.

Figure 3 illustrates a typical difference between an axle detection signal before and after processing.

3.4 FAD efficiency

The new axle-detection setup for beam-and slab-bridges, with axle detection strain transducers attached to the top flange of the beam, and optimized signal processing considerably improved reliability of FAD axle detection. On the VA0030 Bridge only 3 of 542 axles, in one of the 122 reference vehicles, were misdetected. Similarly, on the bridge VA0028, only 3 out of 778 axles, in 3 of 178 vehicles were misdetected.

4. Improvements of B-WIM Algorithms

This section describes other BridgeMon improvements that have already been implemented into the SiWIM® software and system installation.

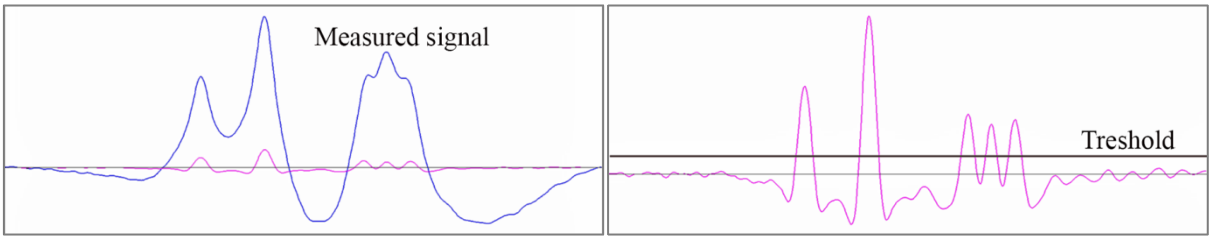

Figure 3 – Axle detection signal before (left) and after processing (right)

4.1 Influence Line Calculation

The majority of B-WIM algorithms use influence lines (IL) which describe the response of the bridge at the measuring location. They can be derived using theoretical principles, but it has been shown that they seldom describe the true behaviour of a bridge (Žnidarič, Lavrič, & Kalin, 2010) and that B-WIM needs ILs calculated directly from the measurements. Two methods for calculating the IL from B –WIM measurements exist:

- the *matrix method* uses trucks of known weight and configuration and performs a linear optimisation to find the IL ordinate at each location across the bridge which provides the best fit to the measurements (OBrien, Quilligan, & Karoumi, 2006).
- the SiWIM® method performs a non-linear optimisation, using trucks of unknown weight to calculate the shape of the IL line. The difference between the measured and the calculated bridge responses is minimised, which is done through variations of the ILs combined with measured axle spacings and loads.

Details about the latter IL generation procedure are given in (Corbally, et al., 2014). Figure 4, left, displays typical results in a screenshot generated by the software. The small pictures list the individual ILs due to vehicles running over the bridge. The top window averages the ILs based on two criteria:

- lanes of traffic; in this case only vehicle runs from lane 1 were used; and
- dispersion of individual results; the standard deviation is used as a statistical parameter to exclude the outliers that result from the numerical procedure, noisy or otherwise problematic measurements, etc.

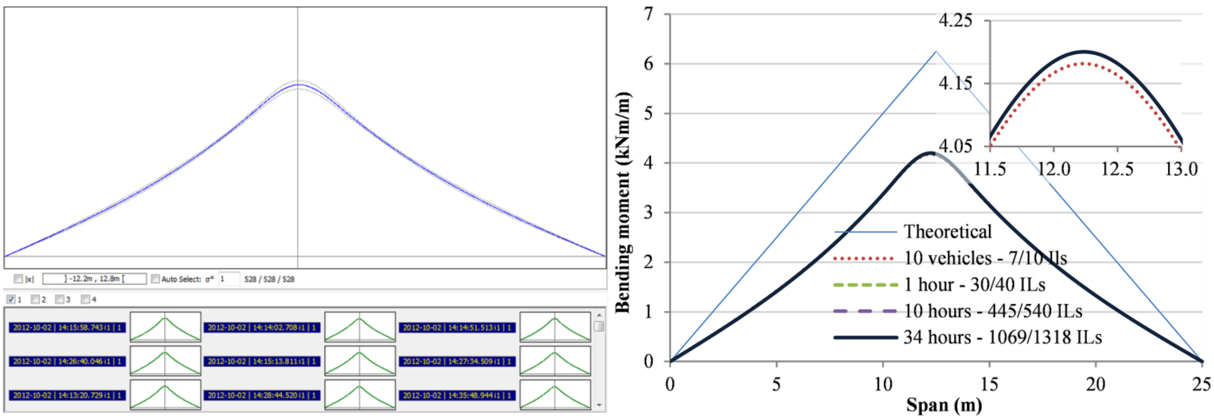

Figure 4 – Generating a 25-m influence lines in SiWIM® software (left) and detail around the peak

The thinner lines in Figure 4, left, depict ±1 standard deviation boundaries of 528 influence lines. The narrow margins indicate that the results are consistent and that the algorithm used is robust. This is illustrated in Figure 4, right, which presents results of averaging of:

- 10 influence lines,
- 1 hour of influence lines,

- 10 hours of influence lines and,
- 34 hours of influence lines.

Within ±1σ there were 7, 30, 445 and 1069 ILs respectively, or 70% to 82.4% of all ILs generated in those periods. It should be noted that even the IL averaged from only 7 vehicles is just marginally different than the rest (see detail of the peak in to top right corner of Figure 4, right). Similar results were obtained on other sites which yield the conclusion that the new method is sufficiently reliable not only to evaluate the ILs for B-WIM measurements but also to monitor their evolution as a part of bridge monitoring process (McRobbie, et al., 2014).

4.2 Calculation of Sensor Factors

On steel elements strains can be acquired with strain gauges, but in most cases detachable strain transducers are mounted on the soffit of the bridge superstructure. A properly setup B-WIM system should measure realistic responses of the bridge under vehicle loading that shall lead to axle loads within a few percent of their statically weighed values. Yet, on reinforced concrete bridges the accuracy achieved is often below expectations. The common reasons are:

a) *Sensor attachment* that depends on the skills of the technician.
b) *Effect of cracks* in reinforced concrete structures. Instead of measuring the global strains of the structure, a transducer captures the local strain response, which, depending on the crack position can be several times higher or lower than expected.
c) *Quality of the sensors* themselves, primarily their production and calibration.

As an illustration, the diagram in Figure 5, left, displays the average maximum amplitudes of normalised strain transducer responses calculated from over 150,000 heavy vehicles captured on bridge VA0028. Clearly, the measured response does not follow the anticipated transverse distribution of strains in a slab. The maximum response was measured by the sensor number 8 regardless of whether the vehicles were driving in the main or in the overtaking lane. A subsequent check revealed that this transducer was placed over a 0.2 mm wide crack.

Such sensor inputs should be corrected. This can be done as a trial-and-error procedure, where gauge factors of individual sensors are varied until a reasonable distribution of strains is achieved. In the case of VA0028, the channel 8 was multiplied by 0.34 and some other channels were also slightly adjusted (Figure 5, right).

Naturally, the trial-and-error approach is not optimal and leads to subjective results. Therefore, an automated procedure was developed. It applies a smooth shape function that approximates the measured and statistically evaluated lateral distribution of the strain response of the bridge superstructure. Details of this method (Žnidarič, Turk, & Zupan, 2015) exceed objectives of this paper.

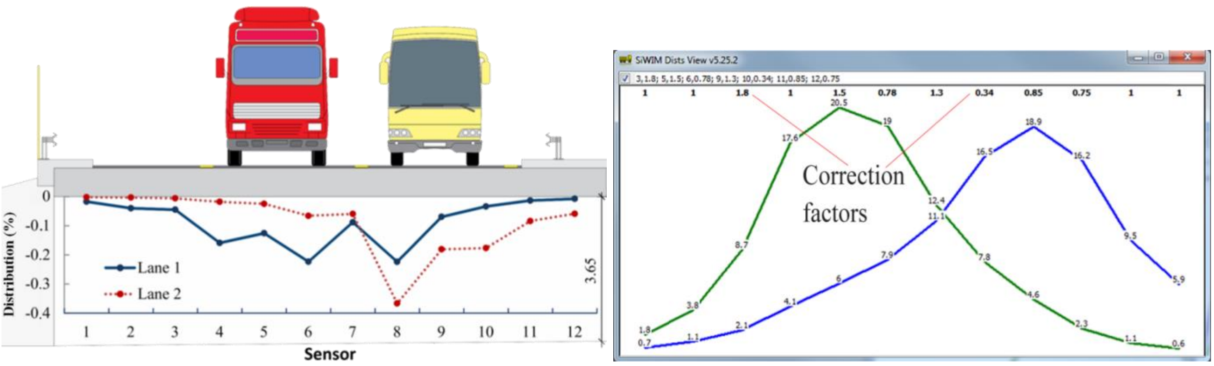

Figure 5 – Cross section of one half of the motorway slab bridge with average responses of twelve strain transducers (left) and sensor correction (right)

4.3 Temperature effects

The response of most bridges to loads is affected by environmental impacts. For example, the effect of temperature on the strains due to traffic loads is mainly reflected in two ways:

1. On integral structures, where displacements and rotations of support are constrained, the influence lines may change with temperature.
2. Material properties (stiffness) vary with temperature. This applies to steel, concrete, and above all, the asphalt, in particular at high summer temperatures. For example, according to the Model code for concrete (fib, 2010), modulus of elasticity of concrete, which directly influences the measured strains, varies by around 0.3% per °C.

In many cases, due to complexity of the structures, compensation of temperature effects is not a straightforward procedure. A procedure was implemented that evaluates dependency of statistically derived relationship between the average gross weights or first axles of the vehicles, and corresponded measured temperature. A correction function is applied that compensates in real time the temperature dependence of results.

4.4 Influence of Velocity on B-WIM Accuracy

Vehicle velocity is another key factor that affects accuracy of B-WIM measurements. The reason is the dynamic excitation of the vehicles that is induced by the unevenness of the pavement surface. This is exhibited by low frequency body bounce of the vehicles, typically at frequencies around 1 to 3 Hz and, axle hop, with frequencies around 10 Hz (Cebon, 1999).

On the approach to bridges this dynamic excitation tends to amplify due to potholes or settlements. Relatively accurate description of this effect can be performed with advanced Finite Element modelling, but the procedure is time consuming and the input parameters (vehicle mass and suspension characteristics of random measured vehicles in relation to their type and velocity) are difficult to assess.

The demonstration below illustrates this effect on ideal simply supported bridges. Dynamic responses of 15 000 2-axle rigid, 3-axle rigid, 5-axle semi-trailers and tractor-trailers, driving over bridges of different lengths, were simulated using measured characteristics of such vehicles:

- mean values and standard deviations of axle spacings and axle loads, and
- values of Dynamic Amplification Factor (Kalin, Žnidarič, & Kreslin, 2015).

Bouncing and axle hop frequencies of vehicles were taken as 1.5Hz and 10Hz, both with 10% coefficient of variation. The amplification of vibration, in % of static loading, was taken from the Gumbel distributions of measured DAF values, separately for 2- and 3-axle and for 5-axle vehicles. Source of data were app. 850 000 vehicles collected on Slovenian motorways. The integrated total responses (Figure 6, left) either over- or underestimate the static responses, a difference that is directly related to the measurement error.

Figure 6, right, summarizes the results for 15 000 simulated vehicles. The average errors (thick lines) and their spread (thinner lines) not only vary with bridge span but also:

- depend on the type of the vehicle, which justifies selecting different calibration factors for different types of the vehicles and,
- variation of errors due to the bridge-vehicle interaction is in the range of ±2% for spans over 15m and gradually increases to over ±5% for shorter spans.

These errors have limited effect on traffic load modelling which is based on thousands of results but are important when accuracy of individual result is looked for, like preselection of potentially overloaded vehicles or accuracy evaluation of the WIM system.

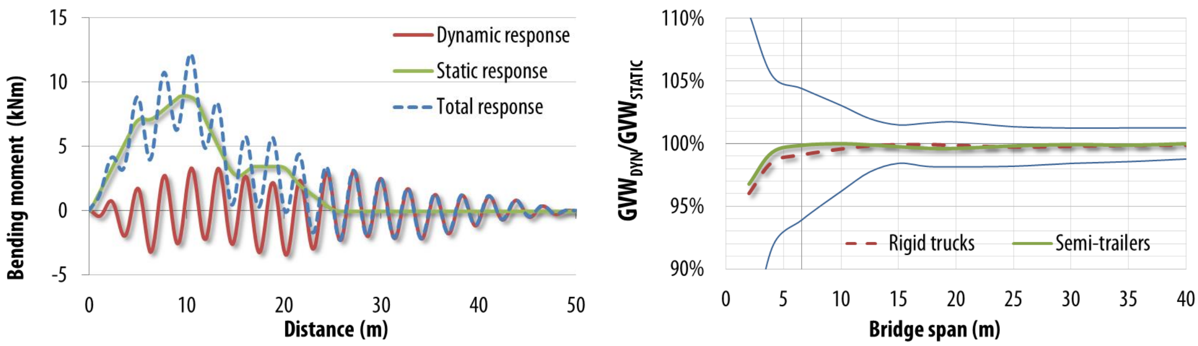

Figure 6 – An example of modelled dynamic response of a 5-axle tractor-trailer on a 10-m span (left) and summary of results for 15 000 simulated vehicles

5. Summary of BridgeMon results

Results from bridges VA0028 and VA0030 were used to validate accuracy of the system prior to the start and at the end of the BridgeMon project (Corbally, et al., 2014). Over more than a year 178 vehicles were statically weighed on a rest area close to the bridges. On the 6-m long slab bridge the long-term results improved for four accuracy classes, from class E(35) to C(15), according to the European WIM specifications (COST 323, 2002). While the accuracy class C(15) was a significant improvement over the pre-BridgeMon version of B-WIM it was shown that even more accurate results on this bridge were prevented by the presence of a bump at the entry to the bridge. Results confirmed importance of not only choosing an appropriate bridge but also of ensuring that the road profile is sufficiently smooth (Lavrič, Žnidarič, & Kalin, 2008).

Results from the 20m beam-and-slab bridge were more pleasing. A two classes increase in accuracy was demonstrated, from D+(20) to B(10). Furthermore, it was shown that when ignoring the sub 6-ton vehicles, which are less important from the infrastructure perspective, the system was capable of achieving accuracy class A(5) for gross weights. This is still rare in WIM technology and represents enormous progress in the field of Bridge-WIM, particularly considering that the results were attained over a long monitoring period.

6. Data Quality Evaluations

The B-WIM system used has a unique capability to store measured strains and all information accumulated along the weighing process. This allows to check, re-evaluate, correct and finally accept or reject the potentially erroneous or suspicious data. Typical corrections are:

- adding missing or deleting ghost (non-existent) axles,
- adjusting position of misplaced axles,
- merging of long vehicles recorded as two or splitting two vehicles recorded as a single one, etc.

Software written Python language detects and corrects most of these anomalies automatically by post-processing the vehicle-by-vehicle files. Then, having the strain signals stored, the vehicles are split into subsets according to the maximum induced strains. The purpose of this phase is to divide the important heavy from the less important lighter vehicles and, consequently, to spend less time for detailed data quality checks.

In the third phase the data quality assessment (QA) is performed. Vehicles are flagged while running through a number of procedures that search for errors and unexpected results. The primary quality indicator is the square of the differences between the measured and calculated strain responses, or the *reduced chi-square* (RCS) factor, which is calculated for every vehicle as a part of the weighing procedure. Then search for the unexpected results is performed. Rules are similar to those recommended in projects ARCHES (2009) and BridgeMon (Corbaly, et al., 2014). Higher the RCS factor and more outstanding the results (very short or very long axle spacings, very light or very heavy axle loads etc.), higher QA value is attributed to the vehicle. Based on the sum of QA values a vehicle is sorted into the green, orange or red subsets. The green vehicles are typically over 90% and do not need further attention. The red ones are in the range of 1% and include extremely heavy and likely erroneous vehicles that should be approved, corrected or rejected on one-to-one basis. The remaining orange ones include less reliable vehicles which may be questionable but likely have no or little effect on results of bridge or pavement load modelling (typically, 1 instead of 2 light axles, a missing light axle etc.).

This procedure dramatically decreases time needed to quality check and approve the results.

7. Conclusions

The 2-year research project BridgeMon worked on a number of issues related to accuracy and long-term stability of B-WIM results. The main improvements that have all been implemented within the B-WIM system included new method for generating the experimental influence lines, more efficient procedure for collecting axle load information, correction of temperature and velocity effects etc.

Results were validated by comparing B-WIM results with the results of 178 statically weighed vehicles that were pulled from the traffic flow. On a 6-m long integral slab bridge accuracy improved for four accuracy classes according to the European specifications for WIM (COST 323, 2002) but still reached only class C(15). The uneven pavement in front of the bridge was blamed for that. Results on a 20-m long beam-and-slab span not only demonstrated improvement for two accuracy classes, but also found gross weights accuracy of vehicles over 6 tons in class A(5) which is still rare in WIM technology.

Last but not least, the new data quality assessment procedure added value to the results and has shortened significantly time needed for their verification and approval.

8. Acknowledgment

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BRIDGE WEIGH-IN-MOTION (BWIM): AN ANALYSIS OF BWIM METHOD ACCURACY


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Abstract

Bridge Weigh in motion (BWIM) is a nondestructive to pavement method to calculate the truck characteristics. An overview of the BWIM method using various sensor technologies and data acquisition equipment installed on a single span bridge on Interstate 91 (I-91) in Meriden, Connecticut are presented. This study has shown that there are three patterns that trucks travel in which cause error or inaccuracies in BWIM weight estimation. Effective algorithms are suggested to improve accuracy of BWIM method and to minimize errors in outputs. The effect of a truck's weight on the strain values recorded under adjacent lane is discussed. Application of BWIM sensors for traffic counts of both trucks and cars are investigated. The improved accuracy of the BWIM method allows for reliable, cost effective solution to identifying overweight trucks while remaining nonintrusive.

Keywords: Bridge weigh-in-motion, accuracy, error analysis, truck patterns, traffic counts

Résumé

Le pesage par ponts instrumentés (BWIM) est une méthode non destructive pour le calcul des caractéristiques des poids lourds. Une présentation du système installé sur un pont à une travée de l'Insterstate 91 (I-91) est faite. Cette étude a montré qu'il existe trois cas de passages de poids lourds qui entrainent des erreurs ou des manques de précision dans le calcul des poids. Des algorithmes améliorant le calcul des poids sont proposés. Les effets de la masse du poids lourd sur les voies adjacentes sont discutés. L'utilisation du pesage par ponts pour le comptage simultané des poids lourds et des véhicules légers est discutée. La précision améliorée de cette méthode de pesage permet une identification des poids lourds en surcharge de manière fiable, économe et de manière non intrusive.

Mots-clés: Pesage par ponts instrumentés, précision, analyse des erreurs, forme de poids lourds, comptage du trafic.

1. Introduction

Understanding the dynamic loading on a bridge is crucial to ensure that bridge structures are in functional condition and to maintain a safe transportation network. Bridges have a specified maximum design load capacity that it can safely carry either on a daily basis or for a one time loading. The live load induced by a truck can have a significant long-term effect on a bridge's safe life, so the weight of the trucks need to be monitored to ensure that they aren't overweight.

BWIM uses the dynamic response of a bridge to determine the trucks' gross vehicle weights, speeds, and axle spacing. It was first proposed over 30 years ago (Goble, et al., 1976; Moses, 1979), and continues to improve with the advancement of sensor and data acquisition technologies. A study by the Connecticut Academy of Science and Engineering (CASE) shows that BWIM is a promising nonintrusive technology which should be considered for WIM in Connecticut (Connecticut Academy of Science and Engineering, 2008). Agencies will be able to collect weight data on a more comprehensive network by implementing BWIM technology using long-term bridge monitoring systems. This improved load information on the transportation network will lead to design of an efficient bridge system, functional pavement, and effective highway system. BWIM provides the ability to weigh and screen commercial vehicles in a timely fashion for weight enforcement and to collect the speed, weight and class data for traffic monitoring.

2. BWIM Methodology

The unique method of this project is the use of the second derivative of the measured strain to identify the time it takes for the first axle of the truck to travel from the start of the bridge to the mid-span, t_1(sec) (Christenson et al., 2011). This time is used to determine the truck speed by

$$v = \frac{L}{2(t_1)} \tag{1}$$

where v is the speed of the truck (ft/sec) and L is the length of the bridge (ft). The second derivative of the strain also produces the time of when each remaining axle passes over the mid-span of the bridge; t_2, t_3, t_4 and t_5 for a 5-axle truck. With these times, the truck's axle spacing, x_n, can be calculated as

$$x_n = v(t_{n+1} - t_n), \qquad n = 1,2,\ldots,N\text{-}1 \tag{2}$$

where x_n is the distance between the n-1 and nth axles, and t_n is the time it takes for the nth axle to reach the mid-span of the bridge after the truck first enters the bridge, and N is the total number of axles of the truck.

Gross vehicle weight (GVW) is determined from the method of Ojio and Yamada (2002). This method relates the known GVW of a test truck to the GVW of any unknown as

$$\frac{A_k}{GVW_k} = \frac{A_u}{GVW_u} \tag{3}$$

where A_k and GVW_k are the calculated influence area and reference gross vehicle weight for a test truck of known weight, and A_u and GVW_u are the calculated area and gross vehicle weight for a truck with unknown weight. The ratio of GVW_k to A_k is defined as the calibration constant β

$$\beta = \frac{GVW_k}{A_k} \tag{4}$$

To calibrate the BWIM system on the Meriden bridge, a 5 axle truck with specified weight with variable speed traveled over different bridge lanes. Value of β was calculated for slow lane and middle lane.

Substituting Eq. (4) into Eq. (3) and rearranging provides the GVW of the unknown truck as

$$GVW_u = A_u \beta \tag{5}$$

where A is a function of strain, ε(t). The displacement can be written in terms of velocity and time, $x = vt$, and lastly the equation can be written in discrete form as

$$A(t) = v\int_{-\infty}^{\infty} \varepsilon(t)dt = \frac{v\Delta t}{M}\sum_{i=1}^{M} \varepsilon(i\Delta t) \tag{6}$$

where Δt is the discrete sample time of the strain measurement, and M is the total number of measurements needed for the truck to cross the bridge (Christenson and Wall et al., 2009).

3. Field Test

The Meriden bridge is a three-lane, single span, simply supported bridge that carries Interstate 91 Northbound over Baldwin Avenue. Trucks' data were collected at the Meriden bridge and the nearby weigh station simultaneously on June 5, 2015. The purpose of the field test was to test the accuracy of the previously validated BWIM system on the traffic stream. The accuracy of BWIM method was evaluated by comparing the calculated weight of the truck with that of measured by the static scale at the weigh station. Traffic stream data was recorded when the weigh station was opened in intervals. There were three systems in place collecting data; the Bridge Diagnostics Incorporated STS-WiFi System (BDI), the permanent sensor system, and the weigh station static screen weights. There are a total of 38 sensors including foil strain sensors, piezoelectric strain sensors, piezoelectric accelerometers, capacitance accelerometers, resistance temperature detectors (RTD), and microphone installed underneath the bridge configured as shown in Figure 1. The image stream of trucks crossing the bridge was collected using a camera and processed with MATLAB's Image Acquisition Toolbox. Image collection was synchronized with the sensor's data collection, therefore, a trucks image is associated with its sensor data.

The data was collected when the highway weigh station sign read OPEN. The photos of the trucks along with their corresponding weight were taken at the weigh station. The image and weight of each truck calculated by BWIM method were matched with those recorded at the weigh station.

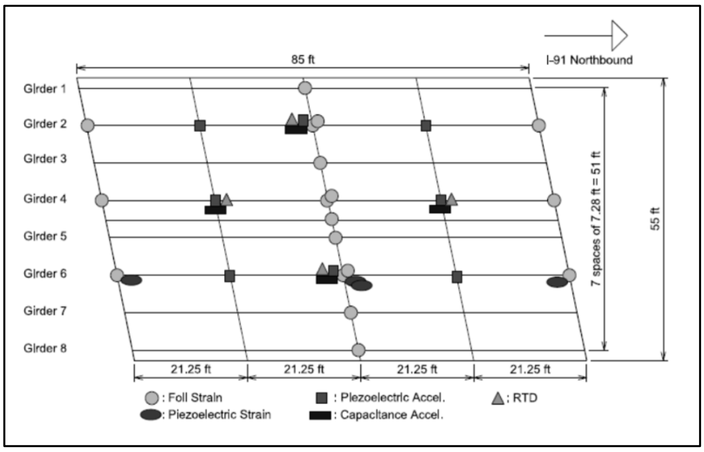


Figure 1- A Schematic of Sensor Layout and Sensor Type for the Meriden Bridge

A total of 250 trucks were recorded between 8:30 AM and 11:30 AM during Weigh station operation time. 113 trucks were matched with their respected weigh station weights. Comparison between calculated and measured data showed that the best accuracy achieved when trucks are traveling around the speed limit (65 Mph). The trucks traveling with a speed range of 45 Mph to 75 Mph were studied due to the increased inaccuracy beyond this range. The total average of the difference between the calculated weight using the BWIM method and the screen weights from the weigh station was -0.74% with a standard deviation of σ= 13%. The average absolute value of this difference was 10% with a standard deviation of σ=8%. There were 101 trucks traveling in lane 1 while there were only 12 trucks traveling in lane 2.

The 113 trucks were traveling at an average speed of 57 Mph. The accuracy of the estimated weight for trucks traveling over the bridge are summarized in Table 1 and shown in Figure 2. The mean difference between the estimated and actual weights, μ, is 0.69% for lane 1 and 13% for lane 2. The standard deviation, s, is 16% for lane 1 and 23% for lane 2. The width of the confidence interval, δ(%), is 6.24% for lane 1 and 26.02% for lane 2. The 95% confidence interval for the mean < μ>0.95, is [-2.43%; 3.81%] for lane 1 and [-0.01%; 26.01%] for lane 2. The 95% confidence interval for the standard deviation, <E>0.95, is [12.88%; 19.12%] for lane 1 and [9.99%; 36.01%] for lane 2.

Table 1- BWIM percent difference statistics for trucks from the traffic stream, by lane.

Lane	# Trucks	μ	s	δ(%)	<μ>0.95	<E> 0.95
1	101	0.69%	16%	6.24%	[-2.43%; 3.81%]	[12.88%; 19.12%]
2	12	13%	23%	26.02%	[-0.01%; 26.01%]	[9.99%; 36.01%]

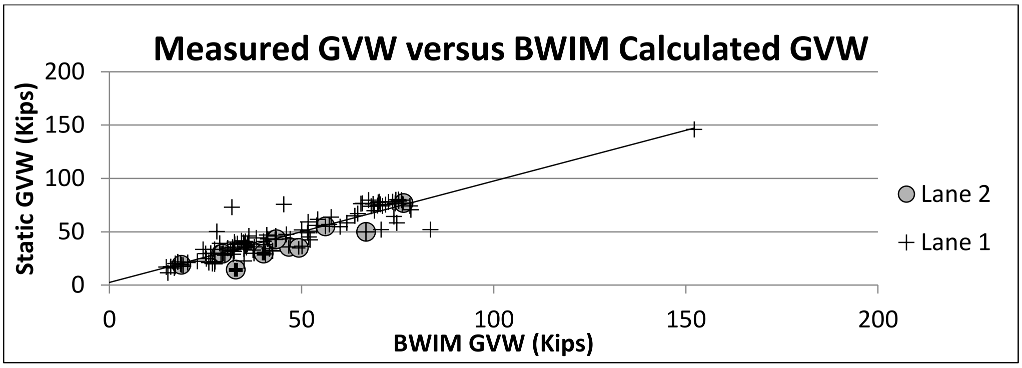


Figure 2- Accuracy of BWIM weight estimation compared to the recorded static weight.

The mean of the GVW difference is 0.69% and 13% for lanes 1 and 2 respectively. The 95% confidence interval for the BWIM difference of the GVW of the 101 trucks traveling on lane 1 is [12.88%; 23.39%]. The 95% confidence interval for the BWIM difference of the GVW of the eight trucks traveling on lane 2 is [9.99%; 36.01%]. The confidence interval for lane 2 GVW measurement difference is larger than for lane 1. This increased interval for lane 2 may be due to the low number of trucks (giving a small sample size) traveling over lane 2. According to the rating system described in COST 323, lane 1 falls in the rating E(35%) and lane 2 falls under the rating E(55%).

The BWIM methodology was unable to calculate the weight of 23 trucks. It was found that the error in weight calculation occurs when trucks are traveling in unusual patterns which cause the speed and weight to be recorded as zero. These unusual patterns are when trucks are traveling side-by-side, back-to-back, or staggered in two lanes. Errors also occur if the truck travels under 30 Mph or over 90 Mph. 48% (11 trucks) of these cases were traveling in lane 1 while 52% (12 trucks) were traveling in lane 2.

4. Shortcomings of BWIM Method

4.1 The Effect of Stain on Other Lanes

When a truck travels over the bridge on a specific lane, it affects the strain on the other lane. This results in a miscalculation of weight if trucks are traveling too close to each other. The collected data showed that If a truck travels in lane 1, the strain in lane 2 will be 37% of the strain recorded under the girder in lane 1. If a truck travels in lane 2, the strain in lane 1 will be 43% of the strain recorded under the girder in lane 1. These values were calculated using the strain histories of 34 trucks traveling alone on lane 1 and another 34 trucks traveling alone on lane 2. This means if a truck is traveling with many cars surrounding it, they could have a combined effect on the strain sensor data of the truck and result in an over estimated weight. This also impacts the strain values when there are multiple trucks on the bridge at the same time. When trucks are traveling too close to each other, an error often occurs resulting in the speed and weight to be zero. More accurate weight estimations can be calculated by eliminating this effect.

4.2 Error Patterns

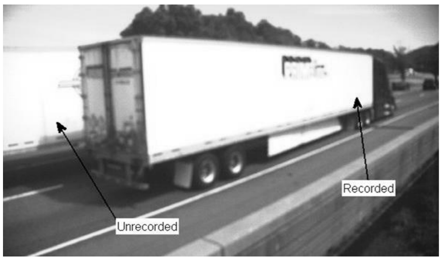
There are three patterns found which cause errors in BWIM calculation. These three patterns include 1) trucks are traveling back-to-back (Figure 4(a)), 2) side-by-side (Figure 4(b)), and

3) staggered in two lanes (Figure 4(c)). Table 2 shows the contributions of each error sources in total errors. Out of 18 total errors, 4 were caused by back-to-back trucks, 3 errors were caused by side-by-side and 11 errors (the most common one) were caused by staggered in two lanes. When the staggered case happens, the first truck typically is recorded by BWIM but because of the second truck entering the bridge within 2.5 seconds, an unexpected strain peak occurs and causes an error in the computational program. Therefore, the second truck is not recorded at all. However, there was one occurrence of this staggered pattern where both trucks were recorded (Figure 4(d)). This specific situation worked because there is a spacing of approximately two car lengths between the two trucks.

Table 2- Contribution of each truck pattern causing errors in weight calculation (%)

Truck Pattern	Percent of Total Errors
Back-to-Back	22.2%
Side-by-Side	16.7%
Staggered in Two Lanes	61%

a) Back-to-Back



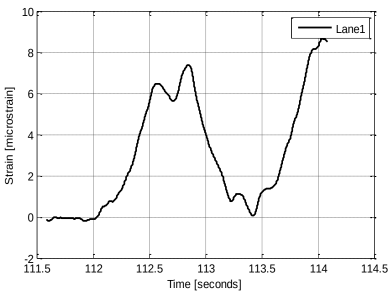
b) Side-by-Side

c) Staggered in Two Lanes

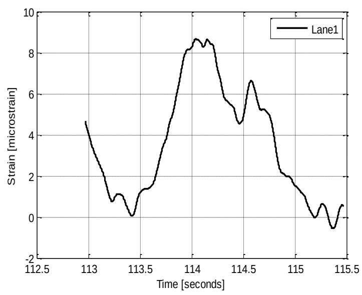

d) Working Staggered in Two Lanes Case

Figure 4 – Patterns that cause errors in BWIM calculation

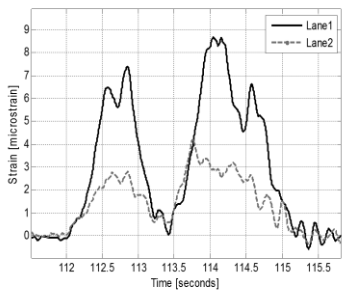
Studying the strain histories of trucks traveling with patterns (Figure 4(a) to Figure 4(d)) will help to develop a proper strategy to prevent the error in BWIM methodology. Figures 5 to Figure 7 show examples of strain graphs of the three error patterns.



a. Truck 1

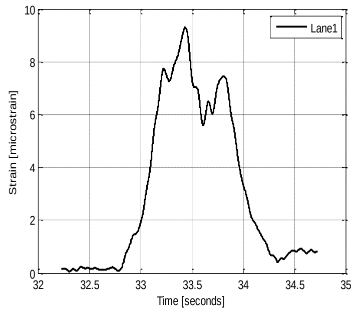


b. Truck 2

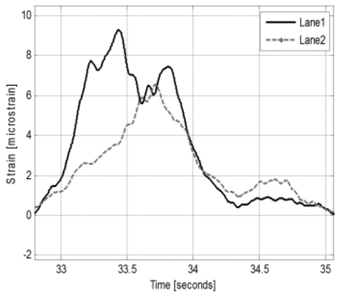


c. Back-to-Back Truck 1 and 2

Figure 5 – Back-to-back strain graphs of two trucks and their strains histories.

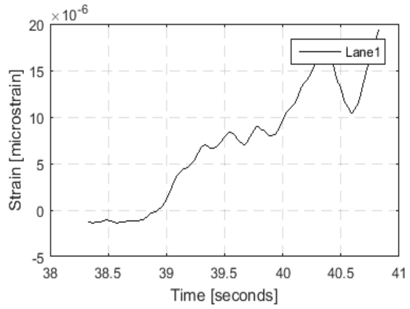


a) Strain graph of truck 1

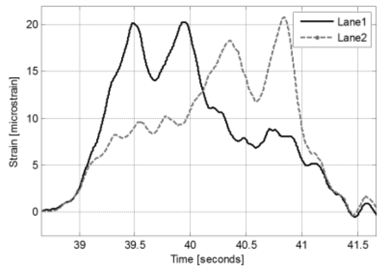


b) Strain history of truck 1 and 2

Figure 6 - Side-by-Side Strain Graph and Strain History



a) Strain graph of truck 1



b) Strain history of truck 1 and 2

Figure 7 - Staggered in two lanes strain graph and strain history.

4.3 Approaches to solving the error causing events

Figures 5(a), 5(b), and 5(c) show the strain for a back-to-back pattern. It can be seen that the code only recognized both truck events separately, but neither of them were properly recorded. The tail of the first truck's strain graph was affected by the beginning of the second truck's strain and the beginning of the second truck's strain graph was affected by the tail of the first truck's strain history. A solution to this situation is to use a shorter time duration to calculate the area under the strain (later to be used to calculate the weight of the truck). By setting the MATLAB code to detect how many peaks occur in the 2.5 second duration (by summing up the results of the 'findpeaks' function), a trigger is set off when a third peak occurs. When this third peak occurs, the program will start over the analysis with a shortened duration of 2 seconds. By doing this, only the first truck's strain peaks are recorded, therefore no other truck peak is captured and an error does not occur.

Figures 6(a) and 6(b) show the strain history of side-by-side trucks which overlap each other. The truck in lane 1 creates a greater strain than the truck in lane 2, so only the truck in lane 1 was triggered by the code. This error can be addressed by setting a condition so that if two lanes are within a certain percent of each other, both should be considered separately. If the strain in each lane is within 80% of each other, the program is triggered to know that two trucks are traveling side-by-side. When this event occurs, the program can run twice, once considering only the strain in lane 1 and once considering only the strain in lane 2.

In Figure 7(a) and 7(b), the strain history of two staggered trucks almost mirror each other. The duration to calculate the area under the strain history starts at the first peal from the truck in lane 1 but only the truck in lane 2 is considered because it has the greatest maximum strain. However, the image of the truck in lane 1 is extracted for this strain history. With staggered in two lanes being the most prevalent error pattern, it is important to be able to distinguish between the two truck events. In order to fix this error, an approach which combines the solutions of back-to-back and side-by-side must be used. The staggered truck events can be caught by comparing the peak strain history of the sensors under each lane. The trucks are staggered if the second truck's strain peaks occur within 2.5 seconds from the first truck's strain peaks. When a third peak is detected, instead of only considering the greatest strain peak, the program runs once considering only the truck in lane 1 and once considering only the truck in lane 2, similar to the side-by-side case.

5. Portable BDI system versus permanent sensor system

After tests were done on the permanent system, a portable system called the Bridge Diagnostics Inc. (BDI) Wireless Structural Testing System (STS-WiFi) was put in place. There were 8 strain gages, 2 nodes, and one base station installed. The sensors are placed at critical locations at midspan, close to the permanent system sensors underneath lanes 1 and 2. This system allows for temporary testing and does not require a permanent computer system at the bridge because it sends the data using WiFi. There are promising results for the BDI portable system data in comparison to the permanent system. The two systems were plotted against each other in MATLAB. While the BDI graphs tended to start at a higher strain value, the values lined up with the portable system. A calibration factor was used for the weight in the BDI code which is 2.207. The results seen in Figure 8.

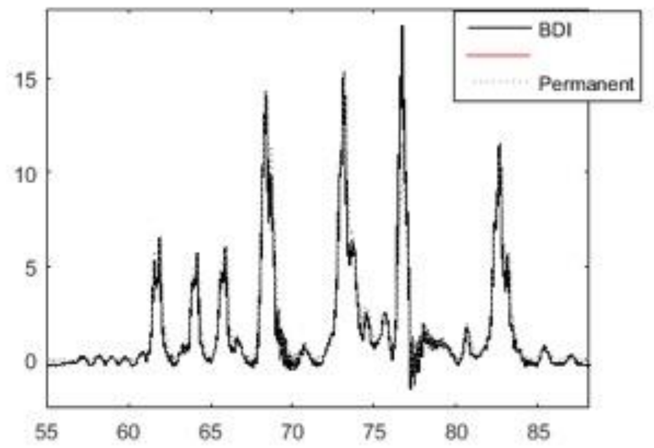


Figure 8 – Permanent data (light grey) plotted on top of BDI data (dark grey).

This plot shows that the BDI system aligns with the permanent system very closely. The BDI showed higher values than the permanent system but this was corrected with a calibration factor on the strain. The average differences between the BDI weights and the actual weights and the average differences between the BDI weights and the permanent system weights are shown in the table below.

Table 3 – Percent difference between BDI and actual and BDI and permanent weights.

Run	Difference between BDI and actual	Difference Between BDI and Permanent
1	-2%	-2%
2	-1%	-6%
3	-37%	-57%
4	12%	5%
Average	-7%	-15%
Standard Deviation	16%	22%

Each BDI record lasted for 6 minutes, continuously recording. Each run is a segment of time when the weigh station was open and the permanent system and static measurements were being recorded. For two runs the results were very good, with only a -2% and -1% difference from the actual weight. For the other two runs the differences were on the higher side.

6. Car counting using permanent sensors

The existing strain sensors can detect strain peaks of all sizes. By isolating strain peaks between the sizes of 2.5 and 5 microstrain, the number of cars crossing the bridge can be estimated. The MATLAB code has ability to count the number of cars for each lane separately. The recorded videos of the traffic displayed 492 cars passed over Lane 1 (slow lane) during the test. The Matlab code estimated 405 cars over the lane 1, which results in 17% error. There were 774 cars counted in lane 2 and 760 of them were estimated using the sensors and MATLAB software, resulting in 1.8% difference. The number of cars in Lane 1 was underestimated by an average of 4.14 cars. The number of cars in Lane 2 was underestimated by an average of 0.67 cars. Higher accuracy in car counting in lane 2 could be due to the fact that more cars are traveling in lane 2 than in lane 1 which could have an effect of the statistics. Also, most of the trucks were traveling in lane 1, so any car traveling close to the truck does not get counted because of the elevated strain peak. Since there were few trucks traveling in lane 2, this problem happens much less, resulting in a better estimation. In order to decrease the effect of the trucks on car estimations, the setting of the minimum peak distance can be lowered when there are higher strain peaks. However, this could cause an over estimate in the number of cars counted.

7. Conclusion

The BWIM method for Weigh-in-Motion technologies shows promising results for a cost effective, non-invasive solution to Weigh-in-Motion. While there are three types of truck events which caused errors in the BWIM method, there are solutions in place to correct and prevent these errors. The BDI portable system has shown to be an effective and reliable way to collect BWIM data, and has the benefits of short term implementation and easy data collection. The sensors put in place for BWIM have also been shown promise to conduct traffic counts. While improvements need to be made on the accuracy of the car counts, the results show that it is possible to so. BWIM technologies can serve multiple purposes and allow for better overweight vehicle identification and easier and more cost effective ways to conduct traffic counts.

8. Acknowledgements

The authors would like to thank the University of Connecticut, the Connecticut Department of Transportation, and the National Science Foundation for their support and funding of this project.

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INNOVATIVE USE OF B-WIM FOR DETECTION OF TAX-EVASION VEHICLES IN BRAZIL

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Abstract
This paper describes Data Tax, which is a support system for goods inspection in Brazilian state borders. The system is the result of an innovative concept in the traditional use of WIM data by applications already well known of weigh in motion technology, such as pre-selection, overweight enforcement, roads maintenance, among others. The use of B-WIM technology in this solution and its technical aspects in terms of identifying the vehicle, processing time, temperature influence and calibration, as well as in terms of benefits to the user, like operational and economic improvements, are the objectives of this paper.

Keywords: Bridge, B-WIM, inspection, taxes, integration.

Resumo
O artigo descreve o DataTax, que é um sistema de apoio à fiscalização de mercadorias nas fronteiras estaduais do Brasil. O sistema é fruto de um conceito inovador no uso tradicional dos dados WIM provenientes de aplicações já bastante conhecidas da tecnologia de pesagem em movimento como pré-seleção, fiscalização de excesso de peso, manutenção rodoviária, entre outras. O uso da tecnologia B-WIM nessa solução e seus aspectos técnicos em termos de identificação dos veículos, tempo de processamento, influência da temperatura e calibração, assim como em termos de benefícios para o usuário, melhorias operacionas e retornos econômicos, são os objetivos desse trabalho.

Palavras Chave: B-WIM, pontes, fiscalização, tributos, pesagem em movimento, integração.

1. Brazilian and Solution Background

Brazilian roads are the primary carriers of freight and passenger traffic. The road system totals almost 2 million km with almost 200.000 km of paved roads. Transporting goods in Brazil is important for the country's growing economy. Every day, thousands of heavy vehicles cross borders between different states within the country.

Due to changes in legislation across state boundaries and in the federal district, vehicles with goods have to be inspected every time they cross state borders. With 26 states and 1 Federal district, crossing the border is quite common, and so are long queues and delays in delivery. All vehicles have to stop at the revenue stations resulting in clogging the parking platform and also both sides of the road before and after the revenue station, thus reducing traffic safety. Heavy vehicles tend to avoid inspection while those carrying no cargo are stopped. This all adds to longer processing times, nervousness within the drivers and requirements for larger parking areas.

The proposed solution is based on the bridge weigh-in-motion system (B-WIM) – SiWIM – used together with cameras, variable message signs displays (VMS), closed-circuit television (CCTV), optical character recognition software (OCR) and custom software system.

To summarize the proposed approach, when a vehicle approaches the border, it passes and is weighed by a B-WIM system. At the same time, overview and full front photos of the vehicle are taken. A license plate recognition system records the vehicle registration number. By finding the appropriate vehicle in the on-line database, its own empty weight is compared to the measured weight. If the difference between the two is less then pre-set value, the vehicle is considered empty and allowed to pass the border without inspection. If the difference between the weights is higher than the preset limit, the vehicle receives request to divert to a revenue station on the border by presenting its license plate number on the VMS and an electronic ticket is issued for inspection of the vehicle. Vehicles stopped at the revenue station are inspected and after successful completion of necessary paperwork released to continue their trip. The electronic ticket is closed, with collected data stored for processing.

For the system to work as accurate as possible, an appropriate bridge has to be selected, which will provide stable output, with high and accurate detection of the vehicles and both complex systems have to be connected to a homogenous working unit.

2. Appropriate Bridges

B-WIM systems can instrument different types of bridges. An important bridge selection factor in the case of preselection role for detection of heavy vehicles on state borders is its ability to perform B-WIM measurements without axle detectors (FAD or Free-of-Axle Detector).

2.1 Span Length

Bridges with different spans can be used as long as strain measurements with sufficient amplitude and resolution are acquired. Longer spans result in more accurate calculation of gross weights, but they will provide lower resolution and thus lower accuracy of axle loads. Longer spans will result in more events with several vehicles on the bridge at the same time, which will have negative effect on accuracy of results. A general recommendation is that optimal span length of bridges used for B-WIM measurements is between 6 to 20 m.

2.2 Boundary Conditions

Bridges are typically constructed as either integral or simply supported. Integral bridges are designed as frames and transfer the bending moments from the superstructure into the supports. The main disadvantage of integral bridges is that they require rather strong reinforcement around the corners and that they are more sensitive to changes of temperature. In contrast, a bridge is simply supported when its superstructure can rotate against the support and does not transfer the bending moments from the superstructure into the supports. Very few single-span bridges behave in this manner. Over time bearings between the slab and the abutment deteriorate, which causes the bridge to behave more like integral bridges.

2.3 Thickness of the Superstructure

The superstructure of slab bridges is usually thin (30 to 60cm) compared to the minimum axle spacing of a freight vehicle. This provides good resolution of individual axle load effects. In contrast, the thickness of girder/deck bridges can be well over 1 meter. Where this thickness exceeds the minimum axle spacing, additional sensors may be installed on the slab between the beams to enhance resolution.

2.4 Structural Type

The acceptable structural types of a bridges for B-WIM measurements can be slab, beam-deck, box girder and orthotropic deck bridges that are either single or multiple span bridges.

The main advantages of slab bridges are being short and slender, they allow for more accurate calculation of single axles and axles of a group which generally increases the overall accuracy class of the measurements. They will be likely more susceptive to temperature, especially if the structure is of integral type.

Superstructure of girder/deck bridges are typically composed of two main elements, steel girders or concrete beams and concrete or steel deck placed over them. By being generally longer than slab bridges they provide more accurate estimate of the gross weights. Strains are easier to measure than on slab bridges since all the stresses are concentrated in beams/girders in longitudinal direction. They are also less temperature dependent.

Measurements on orthotropic deck bridges differ from conventional B-WIM installations. Short secondary spans between cross stiffeners and thin steel deck provide sharp peaks in the strain responses due to a crossing axle and these signals are very appropriate for axle detection. Since orthotropic decks are very sensitive in the lateral direction, more strain detectors are needed in the transverse direction.

2.5 Criteria for Selecting Bridges for B-WIM Measurements in Brazil

There are a few general rules on selecting appropriate bridges for B-WIM measurements. Bridges placed in an open road with fluent traffic and with smoother approaches will give more accurate results. Having more than one heavy vehicle on the bridge at the same time affects accuracy of the results. Analyses show that on roads with less than 1.000 heavy vehicles per day and span lengths below 10 m, less than 1% of such events can be expected. The main restriction in bridge selection for the Data Tax system was the necessity of its proximity to the revenue station. Distances must be sufficient to allow enough time for data processing and message display on the VMS to the driver of the vehicle.

3. Temperature Influence on a Box Girder Bridge

For the system to provide security and reliability for the inspectors, it is necessary that the data reported have a certain regularity, especially regarding the weighing accuracy. The calibration method focuses on gross vehicle weight, because it is through this data that system calculates the weight of the load, crucial information for surveillance.

Keep the margin of error within limits for the most of the time was challenging, especially in the case of Itumbiara revenue station, where the structure used for B-WIM system was an overpass with a box girder bridge. This type of structure is challenging due to its construction form, which has a deck with 1,7 meters deep. Besides that, the temperature variation (both internally and externally) along the structure may cause changes in stiffness levels.

Despite knowing the peculiarities of a box girder bridge structure, a research was made to investigate the effects of temperature on the system performance. Eight temperature sensors were installed in different points of the overpass to monitor the temperature throughout the day. At the same time, there was a static weighing operation of the vehicles that were captured by the B-WIM system. Each session lasted around 40 minutes, weighing 30 to 50 trucks and occurred during the morning, afternoon and night shifts. The purpose of this study was to discover if there is any relationship between the temperature of the structure and accuracy of the B-WIM system in terms of GVW.

It was noted that the relationship between the temperature and the weight calculated by B-WIM does not follow a linear relationship and compensation curve was valid only for a narrow range of temperature variation. Also, there is a delay on response between the real temperature variation and the influence of this change on the weighing calculation.

Knowing the characteristics of the temperature sensor used – accuracy of +/- ºC and fast response time – it were necessary to proceed with an analysis in terms of moving average values. Figure 1 shows the polynomial regression of the temperature values.

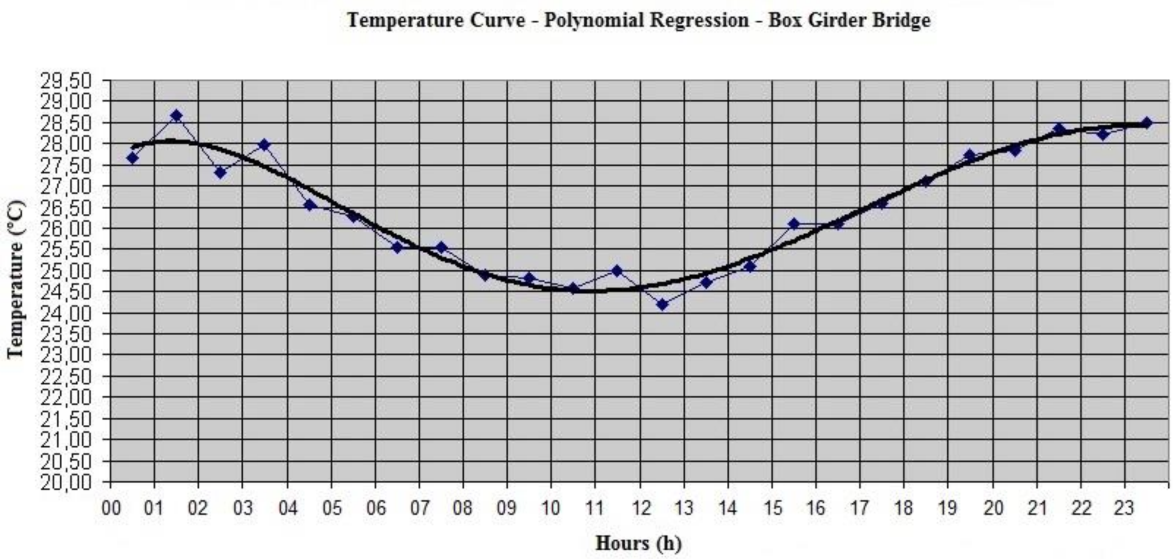

Figure 1 – Temperature Curve of the Box Girder Bridge

A repetitive behavior of the average temperature curve over the days can be observed in figure 2. It was repeated at different amplitudes, regardless of weather conditions.

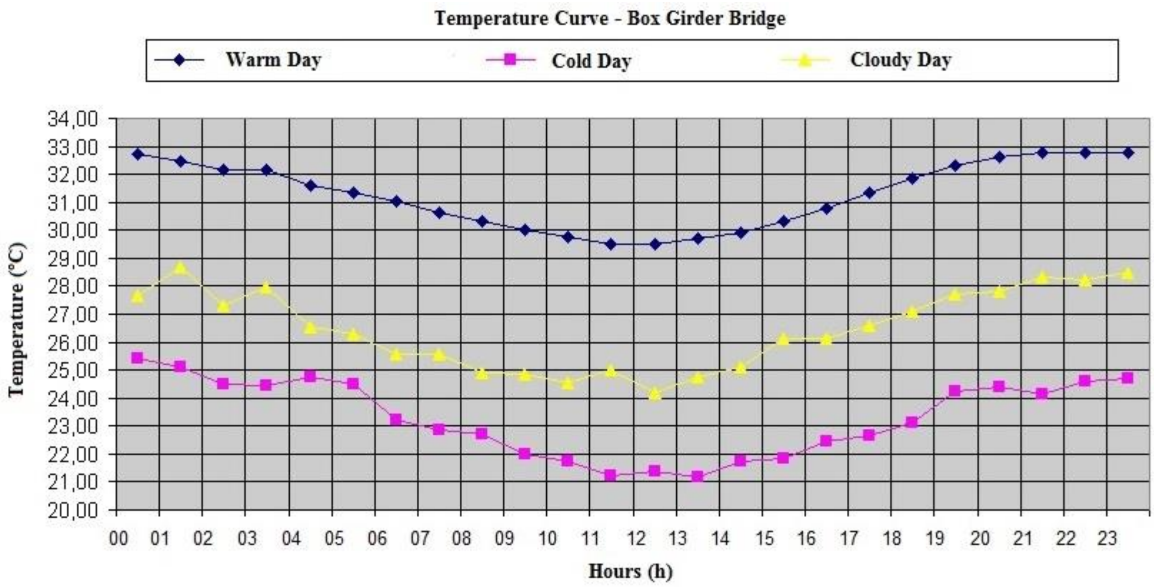

Figure 2 – Temperature Curve in Different Climates

In an initial analysis, we can state that system's gross vehicle weight calculation is inversely proportional to the bridge's bottom slab temperature, i.e., the higher the temperature, the lower the GVW calculated compared with actual value. Such behavior can be seen in figure 3, especially when you compare it with figure 1.

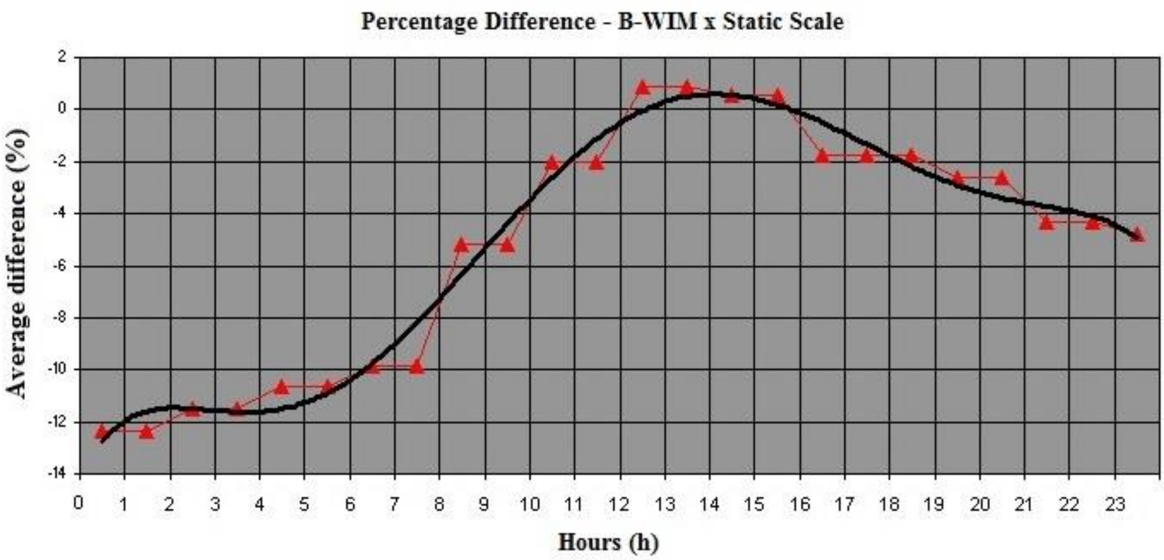

Figure 3 – Average Difference between B-WIM and Static Weighing

The investigation of the possible temperature influence on the weighing accuracy and how to compensate it were only attempts to improve the system performance and to eliminate large variations on the accuracy, so that the system is more reliable for the end user. In fact, the main reason for the difficulty of obtaining consistent results comes from the box girder bridge form of construction and its deck depth.

3.1 Weighing Compensation

After implementation of the study results, a constant monitoring of the accuracy was implemented so that we could create an error compensation curve based on time of the day. The monitoring was conducted by static weighing sessions at different times of day, every day, and allowed us to observe several system performance patterns that were repeated in similar weather days, and therefore we were able to create the indexes for GVW adjustments calculated by the B-WIM system.

Adjustments were established in percentage per hour. Every hour they were adding or subtracting a certain percentage value on the GVW calculated, so that the curve of figure 3 would become as close as possible to a straight line.

3.2 Calibration Factor Feedback

Monitoring through static weighing created a large volume of data that gave us also possibility to use them as input for feedback calibration. Vehicles that had its dynamic weighing under ideal conditions and, afterward weighed on static scale, were subsequently registered as calibration vehicles and, by simulating its weighing on a software, contributed to the improvement of the calibration factors.

This practice led, to new changes of the GVW adjustment rate, but in the long run, it brought great results in terms of reliability of weighing, ensuring GVW accuracy around 5% in most of the time, as shown by the results of one of the static weighing sessions in figure 4 below.

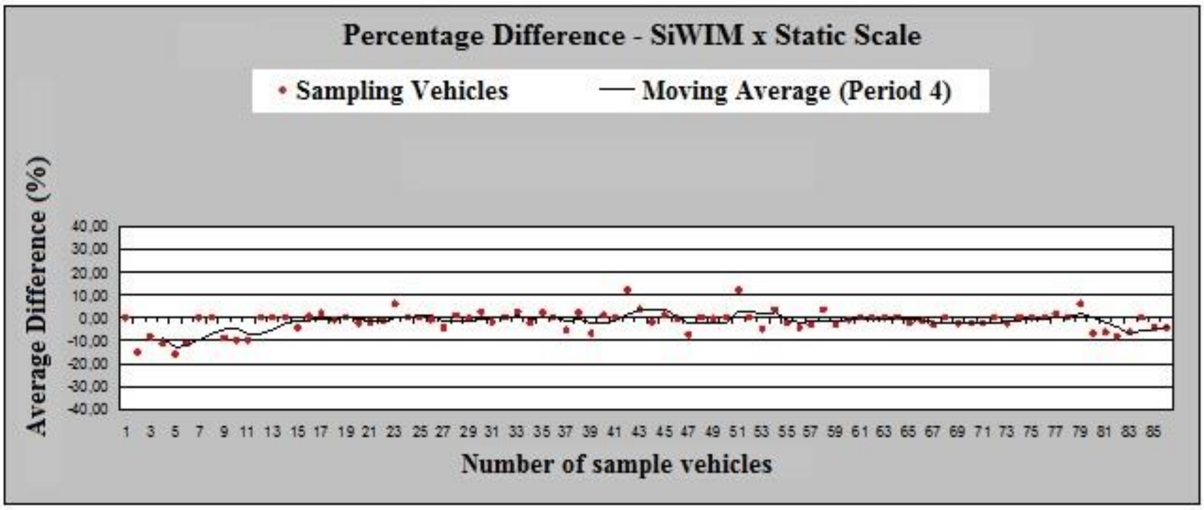

Figure 4 – Average Difference between B-WIM and Static Weighing after adjustments

4. Vehicle Recognition

Axle detection provides information about axle spacing and velocity of the vehicle. WAVE project emerged innovative way of detecting axles directly from the strain signals measured underneath the bridge, known as FAD. The FAD B-WIM installations are considerably more durable, as the sensors are hidden under the bridge and are not exposed to traffic. It also eliminates all actions on the pavement and consequently reduces costs of installation and inconveniences to road users.

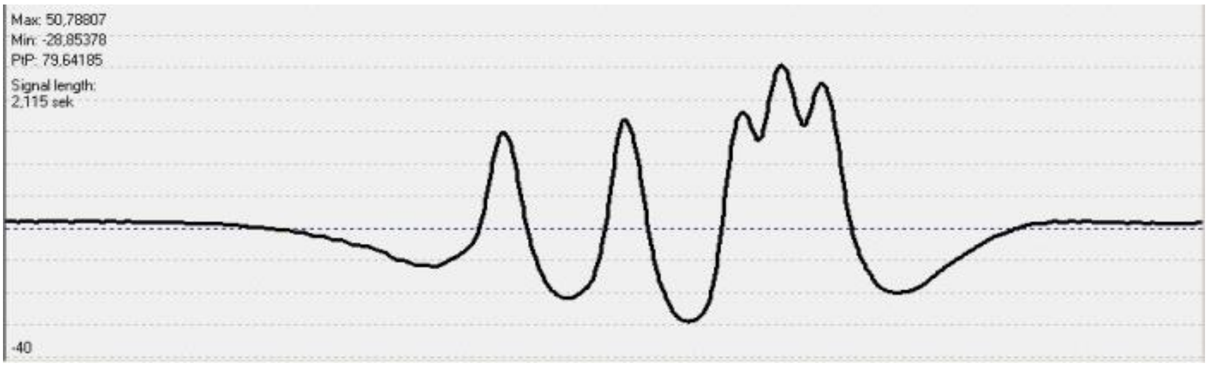

Figure 5 – Measured Strain Responses from FAD Sensors

Figure 5 shows typical strain responses from the box girder bridge in Itumbiara, showed on figure 6. A 57 meter long 3-span bridge, instrumented in the 35 meter long middle span on 50-cm thick slab. Bridge was traversed by a 5-axle semi-trailer. Sharp axle peaks of all axles are clearly seen and there was no sign of dynamic excitation. Since axles were well defined, success rate in the detection of the axles was very high, above 99%.

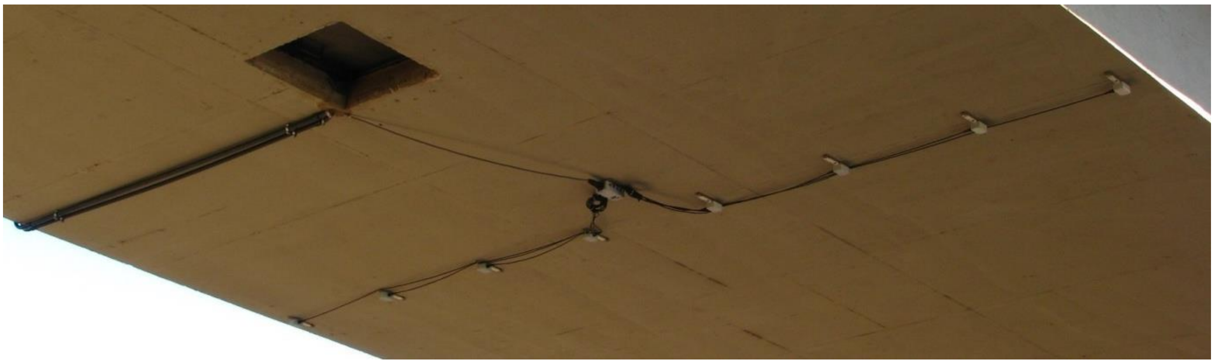

Figure 6 – Weighing Sensors on the Box Girder

4.1 Vehicle Classification

B-WIM systems classify vehicles primarily based on axle spacing. After weighing, classification for some specific vehicle types with similar axle spacings, such as 2-axle trucks and vans, are adjusted based on the minimum or maximum likely gross vehicle weights. Vehicles with longer axle spacings and light axles are reclassified into vans and vice versa. Vehicles are divided into classes, the basic group of vehicles which meets specified axle number and spacing criteria. For example, to be classified into a typical 3-axle gravel truck, first axle must have spacing between 2,20 and 4,00 meters and the second axle spacing between 1,25 and 1,75 meters. Information about all classes is stored in the configuration file.

5. Data Fusion

The integration of WIM data with the license plate data and with a database that contains receipt information from the goods, as well as the integration between the data from the systems of different locations is of great benefit to the end user. The data fusion allows a variety of inspection forms, which were not accessible before. It is possible to identify if the vehicle has a history of fraud, or if the vehicle already has a passage registration from a different location. In this case, it would be possible to see if there was a change in the goods being transported, but without being declared.

A huge volume of data allowed tracing the traffic behavior of certain transportation companies, as well as foreseeing passages based on history and provide information in order to perform specific mobile operations. The information stored by the system can also be shared with the police, municipal authorities, highway administrators and others.

6. Economic Benefits

Operation and analysis, performed in Itumbiara during the sugar cane harvest period where 9-axle trucks were transporting huge quantities of sugar cane for the alcohol plants showed practical use of the system for the government.

The industry trucks had their license plates previously registered in the system, so that they didn't have to enter the revenue station. In just four days of monitoring, the same truck transported a total of 1167.46 tons of sugar cane, although only 887.54 tons were declared. This represents a tax evasion of R$ 2,182.88, corresponding to 24.8% of the cargo. By the end, tax collection from the alcohol industry increased by 54,9% in only one year with the use of Data Tax system.

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USE OF B-WIM FOR MONITORING TRAFFIC ON A SPECIFIC ROUTE IN FRANCE

   

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Abstract

The concept of bridge weigh-in-motion (B-WIM) has been implemented for a few years now in the commercially available system SiWIM. Improvements have been undertaken during the Bridgemon project. Many of these novelties have been programmed and installed in the SiWIM and all these improvements have led to an accuracy class A(5) for gross weights on a beam-and-slab bridge. This updated system has been tested during the Summer 2015 on a culvert bridge at Senlis, on the motorway A1 north of Paris. The class C(15) has been achieved for the real traffic. This solution is of interest for concessionary motorway companies, to assess the number and frequencies heavy loaded vehicles and the induced damage on pavements and bridges.

Keywords: Traffic, B-WIM, bridge, damage, heavy vehicle, traffic loads.

Résumé

Le concept de pesage par ponts instrumentés est développé depuis plusieurs années, et commercialisé via le système SiWIM. Des améliorations du système ont été étudiées dans le projet BridgeMon. Plusieurs de ces améliorations ont été mises en œuvre dans le SiWIM et ont permis d’atteindre la classe A(5) pour les poids totaux sur un pont à poutre. Le système ainsi amélioré a été testé durant l’été 2015 sur un pont cadre à Senlis, sur l’autoroute A1 au nord de Paris. La classe C(15) a été atteinte avec les poids lourds du trafic réel. Ce système intéresse les sociétés concessionnaires qui gèrent les autoroutes en France, pour déterminer le nombre et la fréquence de passage des véhicules les plus lourds et évaluer l’endommagement induit sur les ponts et les routes.

Mots-clés: Trafic, pesage par ponts instrumentés, endommagement, poids lourds, charges du trafic.

1. Introduction

The concept of B-WIM was introduced by Moses (1979). The principle is to calculate axle loads by analyzing measurements from strain sensors installed under the bridge when trucks cross the bridge above the sensors. Moses' algorithm consists of using the influence line of the measured effect to estimate the axle loads, as well as the speed and axle spacing measured apart by road sensors. This simple idea has been improved, and several alternative algorithms have been proposed since then (Quilligan, 2003) for a comprehensive review of these works. In the last years, several other improvements have been tested during the BridgeMon project, and some of them have been implemented in the latest available SiWIM system.

Until now, most of the B-WIM tests and implementations were conducted on concrete integral bridges and beam bridges (Žnidarič, Lavrič, & Kalin, 2010). A few experiments were conducted on steel orthotropic deck bridges (Dempsey et al, 1999; Jacob et al, 2010; Ieng, 2010). In France, at IFSTTAR (former LCPC), both concrete and steel bridges have been used for assessment of the SiWIM accuracy (Schmidt and Jacob, 2012). But concrete bridges with small spans are the most numerous bridges in France, they exist on quite each road and they can be used – with some conditions - for B-WIM.

Therefore, B-WIM is a means to obtain information on the traffic on each road, while being unobtrusive, simple to install and to remove. That is why French motorway companies such as SANEF are interested to test B-WIM systems and then to collect traffic load data.

A first section of this paper exposes the last improvements of the SiWIM system, among which those done during the BridgeMon project. The experiment on an integral slab bridge at Senlis, France, is presented in section 2, along with the COST323 results. Finally, a third section shows an application of this system for traffic screening.

2. History of the SiWIM product

The concept of B-WIM has been implemented for the last 15 years within the commercially available system SiWIM. The most recent improvements have been undertaken during the BridgeMon project that was funded under the *Research for the Benefit of SMEs* scheme of the European Commission’s 7th Framework Programme. One of the main objectives of the project was to achieve higher accuracy and stability of the system, and consequently, to allow shifting from short (up to one month) to long-term measurements. The improvements dealt primarily with the instrumentation and software parts of the SiWIM.

2.1 Hardware and instrumentation

The SiWIM hardware consists of strain sensors, amplifiers, data acquisition and conditioning module, computer, chargers, cabling, cabinet, camera etc. The system comes with up to 32 sensors that measure strains on the main structural elements of the bridge (Figure 1). Typically 5-8 sensors per lane are installed. The measured strains are the main inputs to calculate gross vehicle weight (GVW), axle loads, number of axles and distances between axles (Žnidarič, Lavrič, & Kalin, 2010), of all vehicles crossing the instrumented bridge. Hardware itself has not changed much during the BridgeMon project.

Figure 1 – SiWIM sensors

SiWIM system detects axles indirectly from strains measured on the soffit of the structure, which allows the so-called free-of-axle detection (FAD) measurements. This has positive impact on durability of sensors, which are not exposed to traffic, and consequently on traffic delays and traffic safety due to absence of road blocks needed for installation and maintenance of traditional axle detectors in the pavement. However, due to indirect measurements from underneath the FAD measurements were less efficient on some types of bridges. This has been overcome in the Bridgemon project where more appropriate sensor locations have been looked for, especially on beam-and-slab bridges. Furthermore, selection of most appropriate weighing sensors has been studied. It has been shown that employing only a few of them from under the individual lanes of traffic gives more accurate results than the traditional use of all sensors from across the entire width of the span.

2.2 Improvements achieved in BridgeMon

The most important enhancements achieved in the BridgeMon project included updated algorithms for calculating the bridge influence lines and vehicle axle loads, improved axle detection methods, temperature/velocity compensation and new approaches to quality assurance of results. During the project, several algorithms have been tested. The procedure for automated calculation of influence lines from measurements has been completely reshaped. The existing axle detection and load calculation algorithms have been rethought and optimised and new elaborated analytical methods, like the moving-force identification or the Tikhonov regularization were tested for solving this high-dimensional problem. Moreover, auto-calibration statistical methods have been implemented to account for temperature dependences and dynamic interaction between the vehicle and the structure. Finally, focus was put on methods to check and assure quality of WIM data.

Some of these novelties have resulted in only marginal improvements or were too complex to be built in the commercial system but some others have been programmed and implemented in the SiWIM which has led to long-term accuracy class A(5) for GVW on the test beam-and-slab bridge, a rare achievement in the field of WIM. More details about the SiWIM system and improvements achieved in the BridgeMon project can be obtained in (Corbaly, et al., 2014).

A complete review of the iomprovements performed on SiWIM during the BridgeMon project is given in (Žnidarič et al., 2016).

3. Implementation of SiWIM in Senlis, France

This system has been tested during the Summer 2015 in Senlis, on the motorway A1, 60 km north of Paris. The bridge is an integral concrete bridge, with no skew (Figure 2).

Figure 2 – Bridge A1 PI 48, instrumented with SiWIM

The motorway crosses a small rural road on two parallel bridges with span length of 6.60 m. This span length is well adapted for B-WIM, as only one vehicle can be on the structure in the longitudinal direction. Each bridge supports two lanes of traffic (slow and fast) in one direction. Therefore, the risk of multiple presence exists, when an overtaking of trucks occurs on the bridge; this happens quite often, as the truck traffic on A1 is very high. Even if the newest version of SiWIM has integrated some treatments of these cases, the results are not ideal. Consequently, it was decided to discard the B-WIM measurements in case of multiple presence.

The two lanes in the southbound direction (to Paris) have been equipped with 16 sensors, 8 per lane. Among them, 6 are used for weighing and 2 for triggering the recording and assessing the speeds and axle spacing (Figure 3).

The system has been calibrated with a semi-trailer whose axle spacing and weights were accurately known. Then one full day of measurements was performed with heavy vehicles from the traffic flow, stopped and weighed in static on an approved scale by police and weighing officers. The accuracy of the system was assessed according to the COST323 European Specifications on WIM (Jacob et al., 2002). The innovation was an access to the records of the SiWIM and the corresponding pictures on a mobile phone given to the police officers, who could use the SiWIM autonomously. The visuals are similar to those of WIM stations to which police officers are used to access. The information provided on these visuals is a picture of the vehicle, axle weights and gross GVW, highlighted in case of a non-compliance with the regulation of the country.

The accuracy class C(15) has been achieved for the traffic flow trucks (Table 1).

Figure 3 – Implementation of 16 sensors for monitoring the traffic on 2 lanes.

Table 1 – COST323 accuracy assessment

	Number	Mean (%)	Standard Deviation (%)	Class of the criterion	Global class
Gross weight	15	1.38	3.43	B(10)	C(15)
Group of axles	15	2.27	3.98	B+(7)	
Single axle	30	0.60	7.46	C(15)	
Axle of group	45	2.73	5.83	B(10)	

For GVW and group of axles the accuracy class B(10) is achieved. Moreover, by removing one truck from the sample, whose static weights seem questionable (two axles of a tandem show a 2 t difference), the global COST323 class is B(10).

The investigation is still ongoing in order to determine the parameters that have an influence on the accuracy of the B-WIM results.

4. Proposed mplementation of B-WIM for traffic analysis

B-WIM is of interest for motorway companies in France, such as SANEF. It may help monitoring the heaviest vehicles such as special permit timber vehicles (Figure 4). According to the French regulation (decree of 2009 of the Ministry of Transport), 5-axle timber trucks are allowed with a GVW up to 47 t, and 6-axle timber trucks up to 57 t, on the designed routes. The maximum axle weight remains at 13 t. The impact of these very heavy trucks on the infrastructure is high, while the motorway fee is the same as for other trucks.

Other exceptional loads are carried by truck above the 40/44 t standard limit, such as indivisible loads, with special permits. However, up to 72 t, trucks may have a permanent permit for a 5-year period and an itinerary or a limited portion of the road network. To assess the number and frequencies of such vehicles, and the induced damage on pavements and bridges, road managers such as concessionary motorway companies may be interested using a

B-WIM system. Such a system is almost invisible, and can be installed without difficulty on several points of the network in order to collect data at various sections.

Figure 4 – Timber trucks in France

5. Conclusions

This paper summarises the improvements that have been undertaken on the SiWIM in the last years, and especially during the project BridgeMon. It describes the context and preliminary results of a new SiWIM on a French motorway according to the COST323 Specifications of WIM. The accuracy class C(15) was easily achieved, and even B(10) if only considering GVWs.

It also explains how and why B-WIM can be a good solution for evaluating the traffic loads on motorways and heavily trafficked highways for infrastructure damage assessment.

6. Acknowledgments

The authors thank the General Directorate for Infrastructure, Transport and Sea (DGITM) of the French Ministry for Transport for its great support.

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Sessions posters

IRD VectorSense Technology-Enhancing Traffic Information Systems
Terry Bergan, Carlos Hayler

OIML R-134 Testing and Certification of WIM system
David Cornu, Hans Van Loo

WIM enforcement : Belgium's case study
Benoit Geroudet, Philippe Delmas

Self-sufficient WIM station : Congo's case study
Benoit Geroudet, Philippe Delmas

Metrological support of the weighing of the commercial vehicles
Emil Doupal

Automatic overload control - Road tests in France
Eric Klein, Eric Purson, Didier Simon

WIM data for investigation of truck weights and dimensions
Livia Tovar, Frédéric Domprobst, Franziska Schmidt, Bernard Jacob

Part II: PIARC TC B4 Workshop

Multimodal policies and sustainable, safe and energy efficient road freight transport

Session 1 : Increasing Eco-efficiency of Freight Transport
Chair: Annelie Nylander (Trafikverket, Sweden)

Road freight transport management for sustainable and liveable cities

Eiichi TANIGUCHI (Japan), Yoshikazu IMANISHI(Japan), Jonathan JAMES (UAE), Rick BARBER (New Zealand), William GARDNER (USA), Toril PRESTTUN (Norway), Dave HENRY (Québec, Canada)

Abstract

This paper presents road freight transport management (RFTM) systems for sustainable and liveable cities based on discussion within WG1 of PIACR TC2.3 during 2012-2015. We highlight the framework, institutional factors and strategy development for RFTM systems and several case studies around the world will be given. RFTM plays important role for improving safety, economic efficiency, environmentally-friendly road freight transport, and quality of life of local residents. We discuss the governance framework of RFTM for officials and interest groups who are engaged in planning, implementing and evaluating urban freight transport policy measures. The governance framework is based on PDCA (plan, do, check, and act) cycles including identifying problems, finding approaches and measures, implementing and evaluating policy measures. Good communication throughout the process is a key element for ensuring successful results.

On the institutional factors it is important to understand how the country is governed on the political level, how transport systems and land-use policies are organized and which organization has the jurisdiction over the freight transport management. The collaboration between private companies and public organization is critical for efficient RFTM, since the private companies depend on the public sector who provides infrastructure, traffic and land-use regulations.

Successful development of RFTM and its strategies incorporate principles: (a) Multi-jurisdictional freight planning, (b) Regional cooperation, (c) Public-private partnerships, (d) Dedicated freight planning and management, (e) Leadership, and (f) Performance evaluation.

This paper also gives case studies in Oslo (Norway), Osaka (Japan), Chicago (US), Adelaide (Australia), and Lyon (France). These case studies indicate that freight plans are common for multi-municipal areas than single municipal area, and these plans

cover not only transport efficiency but also environment and safety issues. A number of cities provide strategies including area for truck terminals, truck routes, truck restricted areas, and loading/unloading spaces on street.

As conclusions, it is needed to establish a framework for RFTM to balance factors of economic growth, environment, and safety. Institutional factors are important for sharing ideas and perspectives of RFTM for creating visions of the area based on public private partnerships. Common strategies for RFTM are practically essential for identifying specific policy measures on urban freight transport for sustainable and liveable cities.

Swiftly Green and GET greener in Sweden

Author(s), Affiliation, Country

Annelie Nylander, Pernilla Ngo Trafikverket Sweden

Key words

Facilitate greener and more sustainable transport measures in the Core Network Corridors in Europe

Abstract

Swiftly Green and GET greener
In 2007, the European Commission launched the concept of Green Corridors in its Freight Transport Logistics Action Plan. The Commission wanted to increase cooperation across national borders and collaboration between society, business and research, in order to create green transport corridors for goods traffic. The goal was more efficient and more sustainable transport and logistics solutions. A corridor comprises solutions for both infrastructure and traffic within a wide geographical area.

In December 2015 Closer and Trafikverket finalised SWIFTLY Green[1], a Trans-European network project that ran between 2013-10-01 — 2015-12-31 with the aim to facilitate the introduction of greener and more sustainable transport measures in the Core Network Corridors in Europe. SWIFTLY Green has received a lot of positive feedback on its deliverables, and is mentioned in the proposed revised work plan for the Core Network Corridor - Scandinavian – Mediterranean, where you can read: *"General developments of vehicle technology, emission regulations, weights and dimensions regulation etc. also could have a significant effect on the Scan-Med Corridor. "Greening" is also an important element of the corridor. Projects such as SWIFTLY Green can provide concrete advice on issues such as reducing noise and air emissions as well as increased environmental efficiency by mode"*

The main deliverables in SWIFTLY Green are the **Green Corridor Development Plan** and the **Green Corridor Portal,** The Green Corridor Development Plan is a document that promotes ideas and provides concrete recommendations and examples of good solutions for European transport corridor coordinators. The Green Corridor Portal contains web-based tools which support decision-makers by proposals for future measures that will have an impact on the sustainability of transport and related emissions. The tools offer the chance to measure emissions data, assess potential transport options, and search relevant measures via a search

[1] Swiftly Green had a budget of € 2,9 M and 13 partners from Europe.

engine. Up until today, about 130 measures are assessed, validated and included in the portal.

The challenge
Logistics is the integrated management of all the activities required to move products through the supply chain. For a typical product this supply chain extends from a raw material source through the production and distribution system to the point of consumption and the associated reverse logistics. The logistical activities comprise freight transport, storage, inventory management, materials handling and all the related information processing.

Workshop - How to create modal shift and get greener transport?
Modal shift from road freight to other modes - primarily rail, but also waterborne transport - is generally viewed as being beneficial to the environment and society, particularly since on average road freight emits greater carbon emissions per tonne kilometre than do rail and waterborne freight. Use of non-road modes may also have other benefits, such as contributing to a reduction in road congestion, and in some cases rail and water can be more efficient and reliable than road.

- Green Corridors has been a European concept denoting long-distance freight transport corridors where advanced technology and co-modality are used to achieve energy efficiency and reduce environmental impact. Is it possible to develop such corridors?
- Can we identify means by which modal shift (primarily from road to rail transport) can be achieved
- Can we determine the barriers that currently prevent further modal shift. To identify how these barriers can be overcome, it can be range of fiscal, regulatory and organisational changes.
-The Green Corridor portal, is it usable? https://greencorridorportal.org/

More Information

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Final conference report, Swiftly Greener
Get Greener application to Trafikverkets research funding (only in Swedish) annex 1

Weblinks
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Energy efficient and CO2-free Urban Logistics in Switzerland

Author(s), Affiliation, Country

Martin Ruesch, Rapp Trans Ltd., Member of PIARC TC B4 Freight, Switzerland

Key words

Urban Logistics, City Logistics, Freight Transport, Green House Gas Emissions, Energy Consumption

Abstract

Starting Point/Challenges/Objectives

Urban freight logistics - dominated by road freight transport - is gaining importance regarding environmental impact and use of energy resources. Trends as E-Commerce, reduction of storage with smaller consignments and increasing number of deliveries and „logistics sprawl" lead to an increase in freight intensity and in an increase in energy consumption per tonne-kilometre and consignment. The Swiss project "Smart Urban Freight Logistics" (2015-2017) addresses these challenges. The project is funded by the Swiss National Science Foundation, the Swiss Federal Roads Office, the Swiss Federal Office of Transport, the Swiss Federal Office of Energy and the cities/regions of Zurich, Basel and Lucerne. The main objectives are to identify the state of the art and key characteristics in urban freight logistics and energy consumption, to identify trends and drivers of change in urban freight logistics and energy consumption, to develop Scenarios 2050 and their impact on the energy consumption, assessment of problems and challenges, requirements for energy efficient urban freight logistics, to identify and evaluate energy efficient and CO2-free urban freight logistics solutions, to develop a Vision 2050 for energy efficient and CO2-free urban freight logistics and to develop an action plan for CO2-free and energy efficient urban freight logistics.

Methodology/Approach

Besides literature review the methodologies used include data analysis (freight transport and logistics data), on line surveys with public and private sector, in-depth interviews, case studies for metropolitan areas, forecasting and scenario building, impact analysis (energy use and emissions calculations, WTW approach), backcasting (to develop the vision) and expert workshops for the verification of the results.

Results (interim Results):

So far the project produced the following results:

- A system landscape on urban freight logistics has been developed for Switzerland to show the elements and components of the urban freight logistics system and their interrelations.

- A target system has been developed to design and evaluate measures in a consistent way (central targets are a substantial reduction of energy consumption, reduction of CO2-emissions and reduction of the use of not renewable energies).
- The actual energy consumption and greenhouse gas emissions have been estimated for urban areas in Switzerland (for the different modes, types of freight traffic).
- Mega Trends and logistics trends have been identified and their qualitative impact on energy consumption and CO2-emissions taking into account a survey with 499 logistics companies and shippers.
- For 2050 a trend analysis and two scenarios have been carried and the impact on energy consumption and GHG-emissions has been estimated.
- Best practices and innovative solutions have been identified and evaluated to make urban freight logistics more efficient and to reduce the energy consumption. Such approaches include logistical approaches (bundling, etc.), cooperational approaches (cooperation between logistics service providers, etc.), technological approaches (use of ICT and ITS, alternative engines, alternative fuels etc.) and regulatory approaches (access conditions, schemes for loading and unloading zones etc.).

Solutions demonstrating high potential for energy efficiency and a high transferability to Swiss urban areas are allocated to the specific challenges in the following table:

Specific challenge	***Solutions with substantial contribution (work in progress)***
Increasing energy efficiency of urban logistics	• Preference schemes for logistics services with energy efficient and CO2-free vehicles (driving innovation degree of suppliers) • Make use of automation, robotics and digitization (incl. ICT) in transport (optimisation of routes and mileage) • Make use of integrated rail/road solutions (e.g. City Cargo Geneva, reducing road use and congestion) • Implement slow logistics schemes (reducing time requirements while increasing consignment size)
Increasing reliability and cost efficiency of urban logistics, Reduction of negative impacts of growing e-commerce	• Make use of bundling strategies and cooperative distribution platforms (higher vehicle and equipment utilisation rate) • Flexibility in pick-up solutions for customers (reducing failed deliveries, unnecessary trips) • Introduce schemes in urban areas which prefer non-truck/van delivery or energy efficient trucks/vans delivery • Autonomous driving (increasing utilisation rate of vehicles, higher cost efficiency in road transports)
Reduction of CO2-emissions by urban logistics	• Use of e-trucks, e-vans and e-Cargo bikes (phasing out of fossil fuels in urban logistics) • Monitoring/controlling of energy consumption/CO2-emissions (incl. cooperation with other actors for bundling)
Provision of suitable space for logistics facilities (from energy perspective)	• Provide dedicated space for logistics activities (in suitable urban and industrial areas) to minimize road mileage and maximize the use of rail and intermodal transport (priority areas for logistics in industrial zones) • Provide locations for multifunctional transhipment facilities • Implementing urban micro-hubs for last mile logistics, also integrating additional service functions (e.g. additive manufacturing)

Optimising national, regional and local framework conditions	• Provide framework conditions which support efficiency and sufficiency in demand (e.g. sharing economy) • Provide framework conditions which support energy efficient last mile schemes • Mobility pricing for vans (and adjustments for trucks) • Provide framework conditions for autonomous vehicles on roads and sideways • Optimise delivery time windows (incl. off-hours deliveries) in inner city areas (harmonized between urban areas)
Influencing decision behaviour of shippers and logistics service behaviour (towards greater energy-efficiency)	• Incentives to acquisition and use of electric vehicles and non-road modes in urban distribution • Negotiate more flexibility regarding delivery / pick up with shippers (sufficiency of suppliers) • Introduce slot/ramp management by shippers and LSP

In the further vision development assessments will be done on solutions focusing also on

- identifying and minimising rebound effects, unintended side-effects of urban logistics,
- identifying and maximising positive spill-over and side effects of urban logistics.

Conclusions (provisional)

There is a need for action to reduce energy consumption and GHG-emission by urban freight logistics – specifically by road freight transport. There are several examples and innovative developments which contribute to these targets. Governmental framework conditions can contribute substantially to implement the most promising measures and solutions.

In the vision development the project quantified urban logistics performance and its impact on energy use and CO2 emissions today (2013), for two concise scenarios, as well as the projected trend development for 2050. The vision for 2050 will consider the quantifiable impacts of identified solutions of best practices and vision elements for urban logistics (with substantial foreseen measures, see table above). The vision targets and the envisaged values for an urban logistics vision are itemised in the table below. Their progression and the relevant solution impacts will be further specified in the action plan (to be developed in 2017).

Objectives of energy Strategy 2050	***Results with substantial contribution (work in progress, potential of vision elements will be quantified)***
Reduction of energy consumption (caused by urban logistics)	The vision (and related action plan) for an energy efficient CO2-free urban logistics for 2050 will reduce the energy consumption caused by logistics from 131 W / Inhabitant (2013, Tank to Wheel) to 25 W / Inhabitant (Tank to Wheel).
Reduction of non-renewable energy resources (caused by urban logistics)	The vision (and related action plan) for an energy efficient CO2-free urban logistics for 2050 will increase the share of renewable energy resources from 5% (2013) to 100%.

Reduction of CO2-Emissions (caused by urban logistics)	The vision (and related action plan) for an energy efficient CO2-free urban logistics for 2050 will reduce the CO2-emissions from 2.04 mln. tons (2013) to 0 tons.

The results can be transferred to other urban areas with similar characteristics as in Austria, Germany and other European countries under consideration of the opportunities of energy production. Potentially a part of the solutions can also be transferred to urban areas with a comparable structure outside Europe.

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11.10.2016/M. Ruesch

Electric Road System Solution for Freight Transport

Author(s), Affiliation, Country

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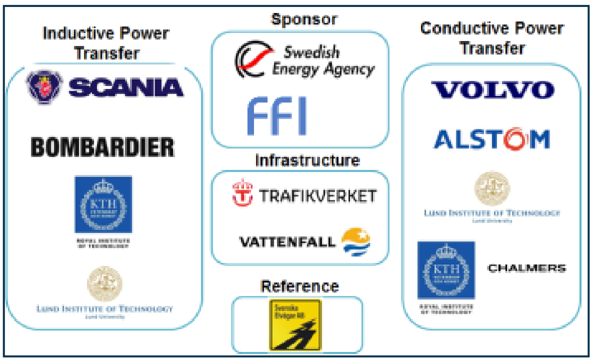
Key words

Electric Road System, Ground feeding system

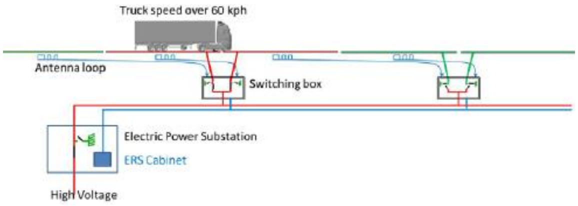
Abstract (1 to 3 pages)

Alstom is a key player in Railways. Since 2003, we are n°1 in catenaryless solutions for tramways thanks to the APS (ground level feeding system) that is in operation in 7 cities (Bordeaux, Reims, Angers, Orléans, Tours, Dubaï and Rio de Janeiro) and under construction in 3 others (Cuenca, Sydney and Lusail). Since 2003 our tramways have run more than 23 000 000km with this technology, and 334 trams &141 km of single track are equipped with APS.

In 2012, in the context of an evaluation of Electric Road System (ERS) solution by the ground initiated by the Swedish Energy Agency, Volvo Truck has trusted Alstom as a partner for the adaptation of the APS system to the road. A demonstrator of conductive solution for slide-in application has been implemented and evaluated on Volvo's test tracks in Sweden.



The performance of the system inherited from tramways allows a power delivery of 1MW to the vehicle, from the grid through 750VDC substations and a segmented slide-in contact. To comply with differences between ERS and tramways, adaptations have been made on the APS system. For instance, the length of the vehicles is shorter and diversified, so the live polarity is applied to a virtual zone in the front and rear of the vehicle only when the vehicle is detected at a minimum speed (60km/h). The number of switching is another difference; it is roughly 200 times higher for ERS than for tramways, therefore the electro-mechanic contactors have been replaced by static switches.



The infrastructure of current collection is made of 3 conductive segments in parallel and adapted to improve the compatibility of conductive segments with road track installation in asphalt and track maintenance and track renovation. Volvo Truck developed the onboard active current collector allowing an automatic lateral positioning of the collector shoe. The tests were passed successfully delivering a slide-in power of 120kW (180 Amps, 690 Vdc) to an onboard resistor bank on the truck at a speed of 80km/h. Slide-in tests with a hybrid vehicle will take place end of 2016 or beginning of 2017.

Current collection test	Result
Continuous transfer at 126 kW / 180 A / 690 V DC	✓
Truck speed over 80 km/h	✓
20 km of continuous power transfer	✓
Rainy conditions	✓
Short-circuit tests	✓
Track adherence tests	✓

For Alstom, this ERS demonstrator was a first step that validates the concept and confirms we can provide an efficient for road truck freight transport.

This type of solution could help very useful to reduce the CO2 emission generated by road truck used for freight transport. This reduction for electric truck vs a thermic truck could reach 90% in France country where electricity is produced with a very low level of gCO2/ kWh. The use of electric truck will help to reduce some others air pollutants like NOx and PM.

The deployment of this kind of ERS is yet an emerging market but we foresee that it would be interesting for several applications like:

- Electric road corridor for road freight transport,
- Electric trucks in cargo harbor,
- Electric buses needing dynamic charging
- Electric dumpers in mine

For Alstom the time is now to go to a step further and to develop efficient product for ERS solutions and to test it in real conditions. This is why we are working on a new project with the objective to build and test an ERS on a section of Highway.

In parallel, Alstom is also developing a new solution called SRS (Static Recharge System) for tramways, electric buses or logistic truck applications. With this system the electric vehicles can be fed in short time on electric charging slots located at stops. Like in APS or ERS, the energy transfer is done from the ground by contact via a retractable collector shoe.

More Information

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- Weblinks:

http://www.alstom.com/products-services/product-catalogue/rail-systems/Infrastructures/products/aps-ground-level-power-supply/

http://www.alstom.com/products-services/product-catalogue/rail-systems/Infrastructures/products/srs-ground-based-static-charging-system/

Session 2 : Use of WIM Data for Highway Traffic Monitoring and ITS

Chair: Lily Poulikakos & Martin Ruesch
(EMPA & RAPP, Switzerland)

Innovative Best Practices for Freight Transport in Europe – Results from the BESTFACT Project

Author(s), Affiliation, Country

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Key words

Freight Transport, Best Practice, Innovation, Europe

Abstract

Starting Point/Challenges/Objectives

In most of the European countries road freight transport is further increasing regarding freight transport performance (in tkm) due to further globalization, spatial division, individualization of demand etc. Capacity gaps on the road network – often caused also by passenger car transport – lead to high transport costs and a negative impact on the environment, high-energy consumptions and an insufficient reliability of freight transport. On main road freight corridors often truck-parking options are not sufficient from the number of parking lots and the standard of the facility. Therefore, approaches for modal shift, a better management of road freight transport and decarbonising freight transport are needed.

BESTFACT – Best Practice Factory in Freight Transport – is a coordination and support action in the framework of 7th Framework Programme funded by the European Commission. It started in January 2012 and lasted until December 2015 (www.bestfact.net). The objectives of BESTFACT were to develop, disseminate and enhance the utilisation of best practices and innovations in freight transport that contribute to meeting European transport policy objectives with regard to competitiveness and environmental impact.

General BESTFACT Approach and Focus

BESTFACT best practice follows a networking and co-ordination approach for a wide range of actors and activities related to innovation and best practices in freight logistics. BESTFACT focuses on the co-ordination and integration of information and know-how on freight transport and logistics solutions. BESTFACT applies a matrix working approach of work packages and clusters. Three thematic clusters are established to identify, collect and process information and knowledge in three particular areas addressing urban freight transport (Cluster 1), green logistics and co-modality (Cluster 2) and e-freight (Cluster 3).

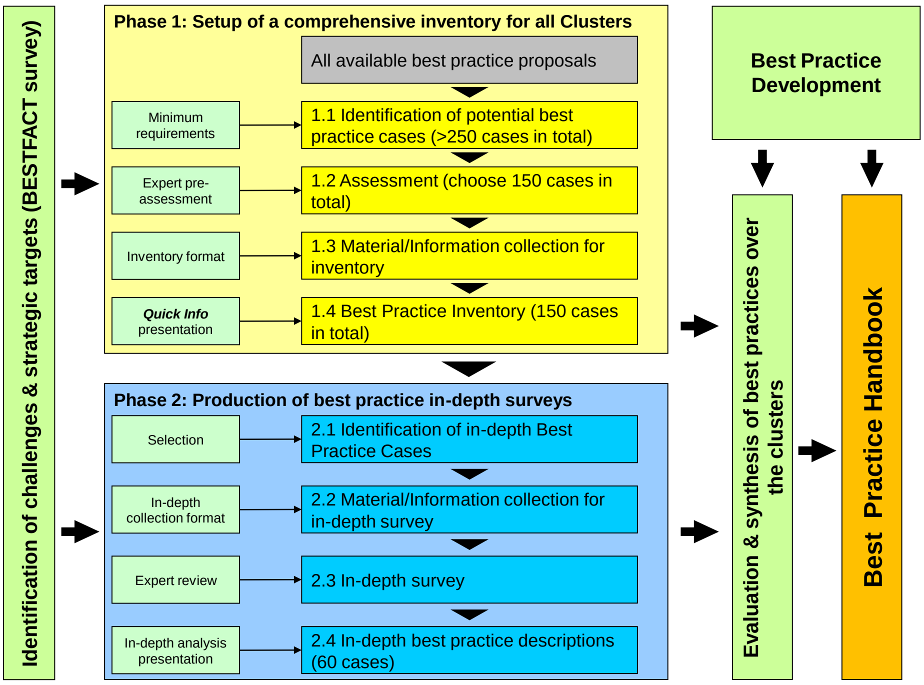
The contribution for the workshop focus on the outcome of cluster 2 on green logistics and co-modality including technology innovations, intermodal services, decarbonising and collaboration.

Best Practice Identification and Evaluation

The central aspect of BESTFACT is the identification and promotion of best practices. Best practice in BESTFACT is considered as an existing approach or solution (industrial business cases, measures, administrative procedures, research results) providing a solution for a relevant problem or challenge in freight transport. It is characterised by the following four core attributes:

- **Innovation and feasibility:** Best practice provides an innovative and feasible approach beyond the common practice. Solutions include products, processes, services, technologies, or ideas that are more effective than previous ones and are accepted by markets, governments, and society.
- **Strategic focus:** Best practice addresses both business and policy objectives. It provides value across actor groups and addresses current challenges and problems.
- **Impact:** Best practices have considerable and measurable positive effects on strategic business and policy targets.
- **Transferability:** Best practice should be transferable to other companies, initiatives or contexts.

Over a multistep process, proposals were evaluated according to the best practice criteria mentioned above. The following charted process steps were defined to collect, consolidate and evaluate current practices and identify good or best practices.



Results

Innovative transport systems and operations are employed to address the challenge of providing affordable and attractive freight services. At the same time, a significant amount of effort is paid for sustainable solutions, promoting greener or shift-from-road solutions.

Numerous initiatives have been working towards that direction: from ports and terminal operators work plans and strategies to European research, studies and works. Over the course of the BESTFACT work in the second cluster 68 cases were described as best practice. These solutions can be grouped to the following four key topics:

Key topics	**Solutions (examples)**
Innovative new technologies	• ENUBA2 – Electric mobility in heavy commercial vehicles to reduce the environmental impact • PARCKR Information system for truck parking • Planzer Operating an E-Force Truck • Intermodal Terminal management system BLU • State border crossing online booking system (EVIS)
Decarbonising	• RECODRIVE - Recognition Schemes for Energy Conserving • Lean & Green initiative • Swiss federal CO2 ordinance applied to freight transport policy • "Objectif CO2" : Voluntary commitments program to reduce CO2 emissions of road freight
Intermodal services and connections	• Cargo Domizil door-to-door transport for general cargo • Cargo-Pendular train with hybrid power operating as a liner train
Collaboration	• CO3 – Collaboration Concepts for Co-modality • SPORTINA - Integrated Management of the Logistics Flow (Sportina Bled Ltd.)

During the workshop selected examples are presented regarding the solution, technical feasibility, the impact, barriers and success factors and their transferability to other framework conditions.

Conclusions

The work in BESTFACT shows how the challenges in freight transport can be addressed and Best Practices in Europe which contribute to a more sustainable freight transport. There are many promising examples regarding the improvement of efficiency and the reduction of environmental burdens of freight transport. The published best practice handbooks give more insight in the impact, barriers, success factors and transferability of around 150 Best Practice cases.

More Information

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ITS Solutions and Platooning for long Distance Road Freight

Bernard Jacob, IFSTTAR, France

Challenges and objectives

Most of the goods are transported by road all around the World on shore, with a modal share varying from 60% (USA, Australia) to 75-80% (EU), and up to 100% in some regions not equipped with railway or waterway. The heavy commercial vehicles (HCVs) are responsible for more than 25% of the CO2 emission in road transport in the EU-28. The road network is also saturated in many regions and with the budget and environmental constraints, it is impossible to significantly increase it. Therefore the capacity, above all for duty vehicles becomes a critical challenge. Finally the lack of drivers in some area, such as in the EU-28, leads to improve their productivity.

ITS (*Intelligent Transport System*) technologies and tools may provide various solutions to face these challenges. On the driver's side, eco-driving may contribute to better energy efficiency and reduce the fuel consumption and the operating costs. Truck platooning as part of the vehicles' automation is also a promising approach to reduce the CO2 emissions and fuel consumption by improving the aerodynamics of the vehicles, to increase the lane capacity, reduce the congestion, and improve the driver productivity. The concept is derived from the railway sector, and consists in grouping small series of trucks into a platoon at short or very short spacing. The vehicles are deeply connected within the platoon but also communicating with the infrastructure and some external centers. The safety issues should be carefully taken into account and the risks mitigated, but the platooning may also improve the road safety by reducing the hazards due to the human behavior.

State of the art, context and data

The development of truck platooning is part of the global process of vehicle automation, and integrated in the AHS, *Automated Highway System* or *Smart Road*, as a main contribution of ITS to the road transport. The first studies and tests on AHS for trucks started in California in 1997 (NAHCS, *National Automated Highway System Consortium*), and continued in Europe (projects Chauffeurs 1 and 2) and in France (project RAPL, *Automated roads for the trucks*, 2002-2004). The European projects SARTRE (*SAfe Road Trains for the Environment*), 2009-2011), and Companion (FP7 2014-2016) led to full scale demos.

3/ Methodologies, idea, techniques and novel methods

The European challenge ETPC (*European Truck Platooning Challenge*), launched in March 2016 by the Dutch EU presidency has the objective to mobilize all the stakeholders and acting bodies contributing to the implementation of truck platoons on the European highways before a ten year term. A partnership between OEMs, parts manufacturers, logisticians, research institutes and public authorities was set up to share knowledge and experience, and to progress in a harmonized way. The works are first focused on the circulating authorization on open roads and across borders, on the truck automation and coupling, the platoon forming, the observation (by airplane) of their behavior, the platoon management and dismantling in motion, the safety and acceptability, the impacts on infrastructure and traffic, and the expected gains, plus the legal aspects.

Electronic vehicle coupling enable them braking or accelerating synchronized avoiding the human time of reaction. That is an automated highway system with interconnected vehicles. There are major challenges such as aerodynamic drag forces reduction and fuel saving, congestion mitigation and reducing the travel times during peak hours, less stress and fatigue for the drivers and thus the possibility increasing the driving time, and a reduction of the front to rear collisions, thus an improved road safety. These advantages are promizing for trucks with potential economic and environmental benefits.

4/ Results and future plans

Theoretical and experimental results of past studies are reported. First results of the ETPC and of the demos carried out in April 2016 are compared with the objectives of fuel savings by road freights transport as claimed by the European Union in its White paper (2011), taking into account the trend of the freight transport demand.

According to a study carried out by the TNO (The Netherlands), the most significant benefit of platooning in the EU may be the increase of truck drivers' productivity, up to 65% of the total gain. This is assessed with some hypotheses on the driving time by law in platoons.

Some on-going or planned deployments for the next years will be suggested, with beneficial and risk assessment, impact studies and proposed technical and regulatory measures to be implemented, as well as a large scale driver training programme. Measures will also be proposed to mitigate the potential adverse effects.

The use of WIM data for platoon monitoring and management, above all when the loads become a critical factor for the infrastructure, will also be investigates.

6/ Conclusions

The technical feasibility of platooning on the main highways on road corridors seems to be proven, at least for mono-brand platoons, Some research works are planned in a call of H2020 framework programme on multi-brand platooning (ART-03). However, a series of questions and issues remain, on legal and regulation, responsibilities and insurances, impact on road safety and infrastructure, acceptability by other drivers, etc.

European Truck Platooning Challenge: https://www.eutruckplatooning.com/

Session 3 : Multimodal Freight Policies for more efficient and sustainable Freight Transport

Chair: Eiichi Taniguchi (Kyoto University, Japan)

TITLE: International road transport and infrastructure in South America
The border crossing dilemma

AUTHOR: Silvia Sudol Ph. D

AFFILIATION: Argentine Road Association (AAC)

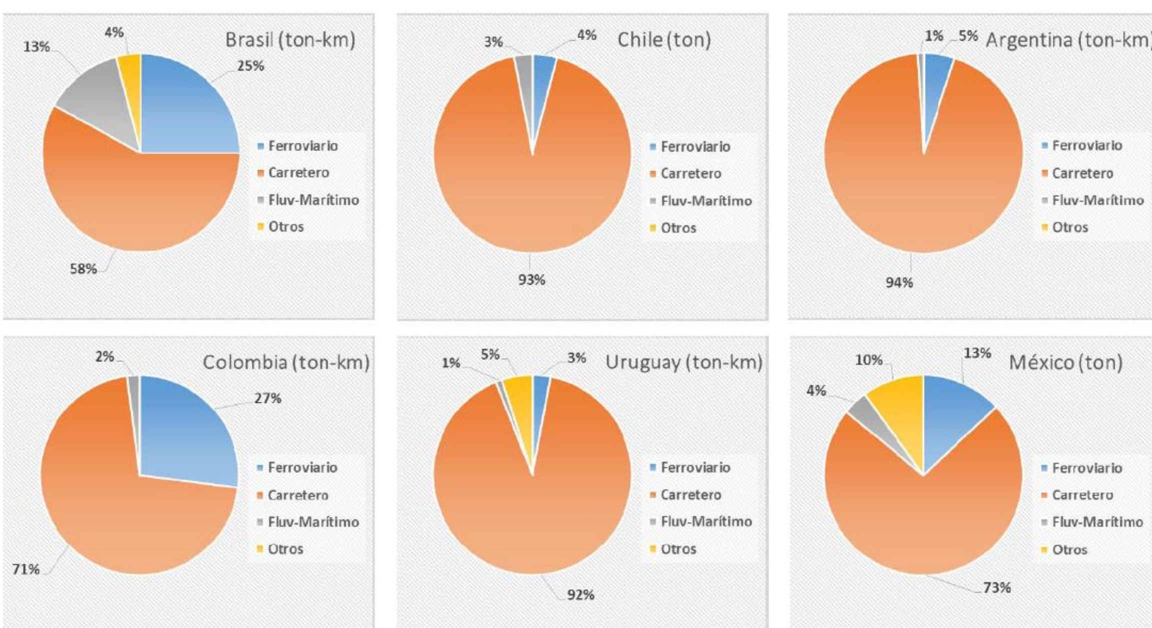
COUNTRY: Argentina

KEY WORDS: border crossing; infrastructure, bureaucracy, integration (software and hardware), Custom, policymakers, speeding up.

ABSTRACT:

General considerations:

Rod transportation even explained 60% of the movement of burdens in Brazil, while the remaining 40% is divided between sea, air, rail, and river. In Argentina, that percentage is much higher, representing the trucking loads about 95% of the transits. On average, these figures are repeated in most of the countries of the region.



Fuente: BID – Observatorio Regional de Transporte de Cargas y Logística

Current scenario:

- significant deficit in infrastructure

- marked territorial imbalance

- strong road profile of transport (where the truck represents more than 90% in the transport of cargo

Latin America "plus" (advantages)

Latin America embodies positive conditions, as a **"zone of peace", but**, much of the region has made very **little effort** in tasks such as **legal security**, **competitiveness**, **efficiency** and strategies for international insertion.

MERCOSUR, (Southern Common Market), particularly, has advanced enough in themes various and broad, but it **has not accomplished significant results in the increase of its levels of trade** (or intra regional and world trade)

The *reduced connectivity* of the region has indeed exerted negative influence in the called aspect: "**hardware**" of integration, which refers strictly to deep deficiencies in infrastructure

However, it is in the "**software**" of the integration process where Latin America is showing the largest deficit to achieve the objective of the streamlining of the transit of passengers and cargo, and regional competitiveness

This problematic software is composed of factors such as:

- Heavy and inefficient bureaucracies
- Regulatory overlap and reduced respect for the guidelines agreed at the regional level
- Protectionist measures intra regional (particularly para-tariff) (non tariff)
- Regularly distorted comprehension of international trends
- Legal security of poor development and reduced national and regional governance
- Absence of statistics or manipulated index
- Systemic corruption
- Cyclothymic public-private relationship
- Funds for transport infrastructure works application "away from the optimum point"
- Low technology (ITS); + Computer systems (WTO/WCO/tracking computer of the transits; Authorised economic operator)
- Look little friendly among different modes of transport.
- Inefficient and slow border crossings.

-

Legal and regulatory support

The fundamental basis of negotiation in the field of "transport" among the countries of the Southern Cone of Latin America is the ATIT ((Agreement of International Road Transport), signed in Santiago of Chile in1989 and put in force in 1990, between Argentina, Bolivia, Brazil, Chile, Paraguay, Peru, and Uruguay.)

The ATIT is also the basis for negotiations on this subject in the MERCOSUR (Southern Common Market), in the framework of the sub-working group N ° 5 "Transportation and infrastructure". (Transport Commission)

Problems of border crossings. The actual “crossroads”

Several examples of Argentine borders problems with its 5 neighbouring countries show these kind of pending tasks linked to delays and inefficency.

Despite the notable regulatory development in the matter during 25 years of the MERCOSUR history and some advances in application of informatic innovations to traditional procedures, according to the proposals of the World Customs Organization mainly, the problem of delays in border crossings remain in South America and the outstanding issues were increasing last years.

Areas such as IIRSA (Initiative of the integration of Regional Infrastructure in South America) and **COSIPLAN** (South-American Council of Infrastructure and Planning of UNASUR) are available for the improvement of the regional infrastructure in **more than one decade ago**. However **still have more projects in portfolio than developed and finalized**. There is a strong duty to be done in this matter, and a big luck in public-private investment to solve.

A greater connectivity between the countries belonging to the region will be an incentive to enhance the competitiveness and facilitate the trade. It is necessary to find the main tools to reach this goals and to have the key to open the minds of policymakers.

This is the field of study of the presentation

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National Logistics Action Plan for Austria

Author(s), Affiliation, Country

Patrick Grassl, Federal Ministry for Transport, Innovation and Technology, Austria

Key words

Multi-modal freight policy, Communication between authorities: cooperation, procedures, legal frameworks; Communication between businesses and authorities: coordination, consultation

Abstract (1 to 3 pages)

Working Group Process and National Logistics Action Plan for Austria

In the "Transport Master Plan for Austria" (which was published in 2012), the Federal Ministry for Transport, Innovation and Technology (bmvit) has set the goals and principles of integrated Austrian transport policy across all means and modes of transport up until 2025. For this purpose, the Austrian transport policy seeks to make the Austrian transport system more efficient, safer, more environmentally friendly and social. Thus, shifting freight transport to more environmentally friendly modes is a clear target of the Austrian transport policy (modal shift policy). At approximately 32 per cent, the share of rail transport in the Austrian modal split is already relatively high by international and European comparison.

The modal shift goal is to be attained by different transport policy measures: For example bmvit supports industrial sidings. Enterprises that want to build or maintain sidings for their plants may apply for an infrastructure grant. Since intermodal terminals are the modern solution to achieve an optimum combination of rail, road and waterway, by 2017, many minor projects and four large rail terminals will be extended and will be open to all rail operators. The bmvit supports this with grants. Moreover, until the end of 2017, subsidisation agreements are being entered into with individual rail operators providing freight transport services by way of single wagon transport, unaccompanied intermodal transport, and rolling road. Hence such funding concerns those types of freight transport by rail that are most exposed to competition on the part of road transport due to their cost structure. Sufficient funds for these purposes will also be available in the future.

The working program of the Austrian federal government uses the Transport Master Plan as the basis for Austrian transport and infrastructure policy. In this context the area of freight transport and logistics is highlighted as a main project area.

Consequently, 2013 - starting from the Transport Master Plan - a common platform for all stakeholders involved in freight transport and logistics was formed and a working group process was launched to substantiate the Transport Master Plan in the area of freight transport and logistics. Since then the declared common goal of all participants from politics, business, science and the social partners is to position Austria as a successful logistics location in Central and Eastern Europe.

By the end of 2014, a logistics action plan was developed by four different working groups:

- WG on road freight transport
- WG on rail freight transport
- WG on inland waterway transport and
- WG on overall logistics (including air cargo)

The success was dependent on the ability of the initiative to integrate the relevant stakeholders into the working group process:

- Public authorities (ministry, funding, administration, social partners etc.)
- Private companies (logistics, forwarders, trade, industry, etc.)
- Experts on logistics and traffic planning
- Universities and research institutes

The institutions involved in the process had the mission to create a comprehensive report as input for strategic planning of the bmvit and to develop concrete measures for a national action plan. The whole process was accompanied by a steering committee that got information on all the activities of the working groups in order to manage the whole process efficiently. Strategic steering meetings were held several times a year and the results and information of the meetings directly influenced the outcomes of the working groups.

By the end of 2014, the "National Logistics Action Plan for Austria" was presented to the public by the Federal Minister. The Action Plan consists of 117 proposed measures, which are the basis of the specification of the Transport Master Plan in the area of freight transport and logistics. The proposed measures form a wide range of viewpoints and are gradually fed into a policy-making process using established technical and political decision-making processes.

This working group process is the first time that a platform for politics, business, social partners and science in the field of freight transport and logistics has been provided in Austria. With the aim to strengthen Austria as a successful logistics location, this dialogue will continue in the future.

Working Committee Logistics

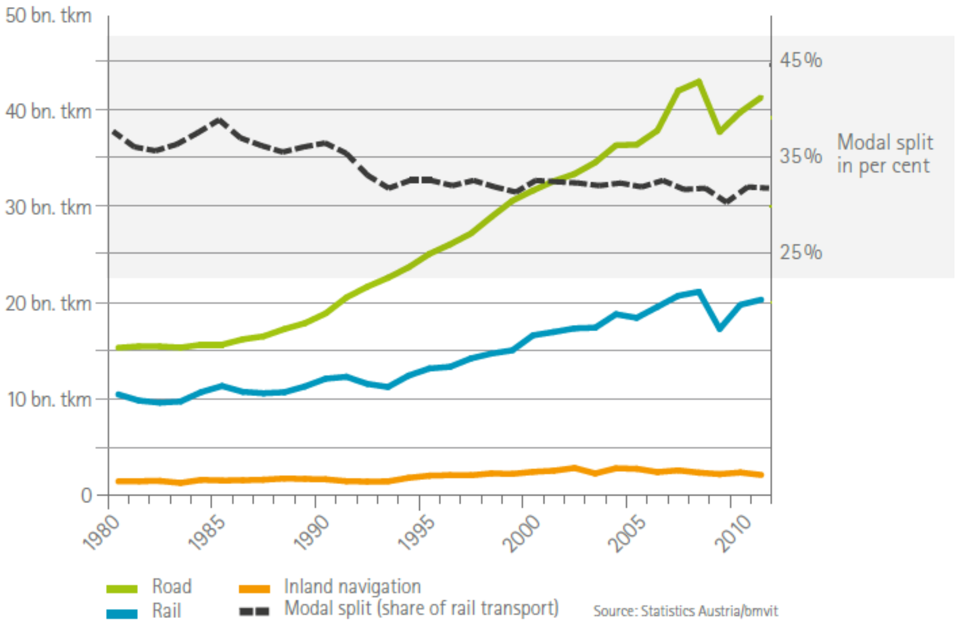
Starting from the working group process to concretize the Transport Master Plan in the field of freight transport and logistics, which was finished in 2014, the first meeting of the so called "Working Committee Logistics" took place in 2015. Building on the positive experience of the past process with its steering committee, the clear aim is now the efficient implementation of the proposed measures through an encouraging cooperation between the relevant stakeholders. The Working Committee is supported by the Federal Ministry and moreover serves as an advisory, informational panel.

Since the beginning of the Logistics Initiative the bmvit – together with the participating institutions – was able to implement several of the formulated measures and therefore increase the competitiveness of the Austrian freight transport and logistics sector as well as ensure social and environmental sustainability.

Examples of implemented measures:

- Appointment of a Federal Commissioner for Logistics Policy.
- Reduction of the costs of truck driver cards for the digital tachograph.
- Revision of the funding program for construction or maintenance of industrial sidings.
- Development of a national R&D Roadmap for the area of freight transport and logistics.
- Support of additional freight transport services by rail operators.
- Revision of the national toll system for vehicles over 3.5 tonnes.
- Establishment of a national communication platform concerning the carriage of dangerous goods.
- Revision of the national strategic concept for intermodal terminals.
- Various measures to improve the rest and parking areas for trucks (real-time parking information, enhanced safety, charging infrastructure).

Development of Freight Transport Volumes in Austria



Members of the Working Committee Logistics

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A transport system that is safe, increases profitability and contributes to the transition into a low-emission society – is it possible?

Author

Else-Marie Marskar, Director General’s Staff, Norwegian Public Roads Administration, Norway

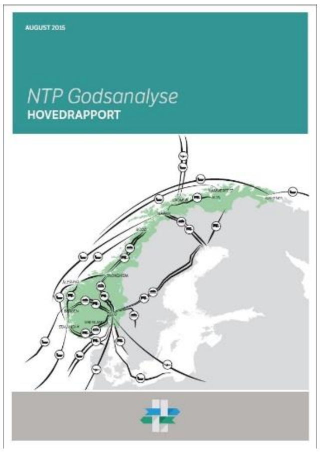
Key words

National transport plan for Norway including strategy for freight transport in a low-emission society

Abstract

A transport system that is safe, facilitates value creation and contributes to the transition to the low-emission society – this is the Norwegian government’s goal and it applies equally to transport of freight and passengers. Transfer of goods from road to sea and railway has been an independent target up until now.

Norway’s global environmental commitments and national growth goals can only be reconciled by making all freight transport safer, more environmentally friendly and efficient - regardless of the means of transport; strategies for freight transport must include - but must not be limited to - the transfer from road to sea and rail – this is the main conclusion from a comprehensive freight analysis that was delivered to the Norwegian government from the transport agencies in September 2015.

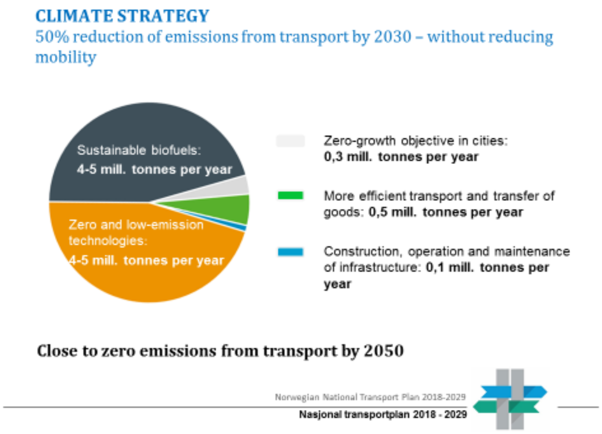


The analysis became the foundation for a proposed strategy for freight transport by the three agencies for transport by road, railway and sea and the company responsible for transport by air. The main implications for are the following:

- Transfer of goods from road to sea and railway where cost-effective
- Strengthen the advantages of each transport mode
- Triple road transport safety by 2030
- Reduce greenhouse gas emissions from the transport sector by 50 percent by 2030 and achieve close to zero emissions by 2050
- Minimise local air pollution from vehicles – close to zero by 2030
- Focus on integrated transport corridors including secondary roads and ferries
- Utilise and exploit ITS (Intelligent Transport Systems) and technology

Lack of infrastructure improvement is not to be used as a means to reduce the demand for freight transport.

A 50 percent reduction of greenhouse gas emissions from the transport sector by 2030 and achieving close to zero emissions by 2050, is possibly the issue that has received the most attention. It contains a number of instruments and measures and the expected impact can be summarized as follows:



- By 2030 almost half the reduction is expected from a transition to vehicles without emissions and more energy efficient motor technology, including a ban on sales of new petrol-fuelled cars, vans and city buses from 2025, later extended to heavy trucks in local traffic and to long-distance vehicles. By 2050, the use of petrol-fuelled vehicles is to be reduced to almost zero.
- Close to 50 percent of the reduction will come from the use of sustainable biofuels.
- Close to 10 percent will come from a modal change (passengers and freight) and smaller emissions from the construction and maintenance of infrastructure.

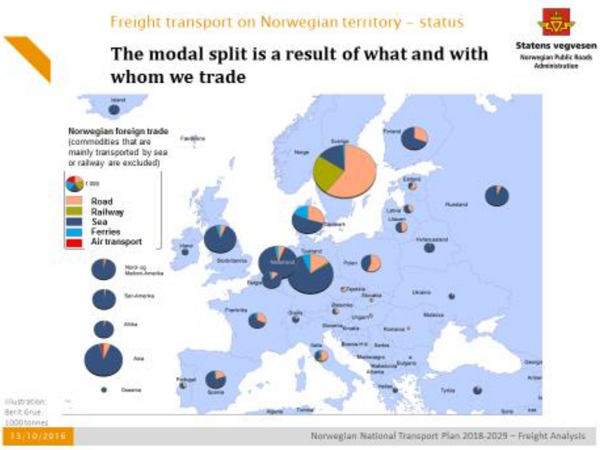
The Norwegian Government is expected to present the National Transport Plan for the period 2018-2029 early in 2017. In the meantime, the freight transport sector has presented their roadmap for achieving zero emissions by 2050 while retaining high mobility. Organizations representing airlines, bus transport, construction, fishing, ferries, forestry, fuel suppliers, harbours and shortsea shipping have committed to the proposed measures and changes. One of the large Norwegian environmental organizations called Zero has participated in developing the roadmap. By 2030, emissions from the transport of freight are to be reduced by 45-60 percent. The instruments and measures and the expected impacts are similar to the transport agencies' proposal.

English summaries of the National Transport Plan and the underlying freight analysis are available here: http://www.ntp.dep.no/English. Some general findings from the freight analysis:

- Freight transport is central to national productivity and value creation and makes it possible even for small countries such as Norway to develop a highly specialized and highly productive industry. Industrial and economic development has resulted in high freight growth.
- Transport of passengers is both an advantage and a threat to freight transport on land. Public interest in investing in infrastructure is high when it benefits people in general, but especially for transport by railways, the time slots are limited and transport of passengers has priority.
- The contradiction between continued transport growth and future environmental requirements makes it crucial to invest in - and implement - new technology. Public authorities must be a driving force in implementing new technologies.

Findings about the modal split:

- The various transport modes mainly operate in different market segments, and competitive interfaces are small. The modal split is a result of what and with whom we trade. The illustration shows the modal spilt in Norwegian foreign trade of goods where road transport is an option. The blue colours represent sea and ferries, the green is railway and the peach is road.



- Maritime and rail transport perform well in market segments with strong competition between transport modes.
- Proximity between freight terminals and industry is important to strengthen the competitiveness of maritime and rail transport, also over shorter distances, but fragmented commodity flows constitute a challenge.
- Reduced delivery time and high frequency are important competition parameters.
- A decentralized terminal structure leads to more goods transported by sea and rail - and less by road, but at the same time more centralized and specialised structures are required to ensure efficiency and low cost. It is the transport buyers' requirements that determine the terminal structure in Norway, especially for transport by sea and road.
- Using maritime and rail transport often involves more complex logistical solutions and organizations than using roads only. Rigid operation of terminals fails to meet the transport market's requirements for flexibility.
- Five to seven million tonnes can be transferred from road to sea and rail in Norway. This will nearly meet the target set by the EU for freight transfer, but the measures needed to achieve this target yield low socio-economic benefits.

Findings about measures, expected impacts and benefits:

- International coordination of taxes is essential for fair competition, and instruments and measures that decrease a nation’s competitive ability are to be used with caution.
- None of the analysed measures will reduce road transport below current levels. Many measures have little effect on the modal split and they generally yield limited socio-economic benefits.
- Measures that facilitate more efficient road transport yield the highest socio-economic benefits.
- Even in a relatively deregulated transport market, the authorities may affect transport development by coordinating their instruments and measures.

More Information

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Session 4: Off-Hours Freight Delivery for more efficient and sustainable Urban Freight Transport

Chair: Tiffany Julien, (Federal Highway Administration, United States)

Title: the road to silent off peak hour's delivery in Belgium

Author(s), Affiliation, Country

Hinko van Geelen, senior researcher, Mobility – Safety – Road Management Division, Belgian Road Research Centre

Key words

Freight Delivery, Urban Freight, Silent Delivery, Off-hours Delivery

Abstract

Policymakers and administrations in Belgium are aware of the necessity to reduce or mitigate nuisances generated by goods traffic, and to tackle all kind of problems encountered by transporters. Especially in urban area, efficient deliveries are essential to improve quality of life. Congestion in the larger Belgian cities is a serious problem, with Brussels and Antwerp in the top 10 European cities for traffic congestion (INRIX 2015 Traffic Scorecard).

In line with sustainable development, goods traffic needs to get greener, safer and smarter. Several efficiency measures can optimize deliveries. A top key measure in Belgium is the implementation of off-hours freight delivery, with silent vehicles and equipment. Five years after the start of pilot projects in the Flanders region, this measure has been seriously considered by all three Belgian regions (Walloon region, Flemish region, Brussels Capital region). Each region has commissioned studies, combining partners from industry, authorities and the academic world. The regions have differences in legislation, especially in the field of noise emissions. This made it interesting for all organisations concerned, to keep an eye on the different study approaches and the results.

In Flanders a pilot project started in 2011 ("PIEK1"). The aim of the study was to examine the social and economic feasibility of quiet deliveries early morning and late in the evening. Two department chain stores planned silent deliveries in 9 cities. The noise aspect was obviously part of the study work, ranging from noise measurements, legal aspects and reactions from residents. A cost-benefit analysis covered different aspects: fuel consumption, time savings, organizational benefits, additional costs (rolling material, stores modification, staff…), environmental impact, traffic safety and accessibility. The study revealed many advantages for both distributors and the neighbourhood, but it became clear that noise legislation needed to be adapted.

	
Inside delivery with difficult manoeuvres.	Moving backwards at the entrance of supermarket.

A follow-up study ("PIEK2") was conducted with a larger scope (5 department store chains, 57 cities). In spring 2016 the results have been presented: an adapted legislation, a roadmap for transporters, a roadmap for local governments, and a guidebook for establishing a dialogue in the field of urban distribution.

	
Noise measurement.	Outside deliveries with potential noise hindrance.

Studies in Brussels-Capital Region and in the Walloon region, both finalized in 2014, had a different approach. The Brussels study was part of "Straightsol", a European Commission supported FP7 project The Walloon case was inspired by the Straightsol approach.

This approach focuses on a multi-actor multi-criteria analysis (MAMCA), in order to take into account different objectives of all stakeholders. Night time deliveries in Brussels were one of the demonstrations evaluated (tests for a month, noise measurements). In total 5 scenarios were formulated to be compared: business as usual, the demonstration, and three scenarios for scaled versions of the demonstration. Analysis suggests that citizens and the department chain stores have similar preferences opposed to the ones of local authorities, but with differences not that big. The goal is to find the right shift to the morning, evening and night so all benefits are optimized.

The pilot projects showed valuable effects :

- The positive effects on fuel consumption and emissions of CO2.
- The impact of traffic safety is positive too, but somehow more ambiguous, as a result of divergent effects. Truck drivers have less stress, mainly because of less congested situations. Manoeuvres at delivery locations are safer too, because there are no customers yet. On the other hand, truck drivers working at night can potentially suffer from fatigue, in particular if it is not regular.
- Business analysis indicates that the benefits outweigh the additional cost to deliver more silent deliveries (trucks, buildings, and other material).
- Acceptance by the public is linked to the situation of the delivery addresses. In general off peak hour's delivery are fully supported, if noise is not deteriorating. Indeed the main hindrance remains the noise, despite several measures taken to decrease the effects. An important barrier to overcome is of legal nature: noise measurements show that environmental conditions are not always be met, unless delivery takes place indoor.

The experiences in Belgium's regions have resulted in valuable lessons worth sharing, including recommendations to the regional authorities, a roadmap for local authorities, and advice to the distribution sector.

More Information

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Impacts of Off-Hour Deliveries: The Cases of New York City, Sao Paulo, and Bogotá

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SUMMARY

The threat of climate change and the health toll caused by air pollution have created enormous pressure to reduce greenhouse gases (GHGs) and local pollutants in urban environments. As one of the largest sources of such emissions, the transportation sector must play a leading role in finding technological, operational, and behavioral solutions to improve urban sustainability. The field of Freight Demand Management (FDM) seeks to induce behavioral changes on the *generators* of freight demand (i.e., "receivers") to increase the sustainability of the freight traffic that is created. Understating the role played by the interactions among shippers, carriers, and receivers in the generation of the various externalities produced is key. FDM recognizes the chief role played by the receivers and, accordingly, seeks to change the receivers' demand to indirectly change the behavior of shippers and carriers, in a way that reduces the externalities produced by the associated freight traffic. In doing so, FDM seeks to induce changes in the timing, number, destination, and/or the mode used to make deliveries. Off-hour deliveries, the FDM program studied in the paper, is one example of inducing receivers to change the time of deliveries. The effectiveness of this shift of focus—from the carrier to the receiver—was demonstrated by the Off-Hour Delivery (OHD) program in New York City (NYC), where a one-time financial incentive of $2,000 induced more than 400 establishments in the food, retail, and accommodation sectors to accept OHD. The success of this implementation, led to pilot tests in such other cities as Sao Paulo (Brazil) and Bogotá (Colombia).

The benefits of OHD include reduced daytime congestion levels, safer roadways for pedestrians and bicyclists, superior reliability of deliveries, lower shipping costs, increased productivity of delivery operations, and reduced emissions. The OHD pilots collected GPS data about the participating companies, which took part in five different research projects. The first two projects are the 2009 OHD pilot test and its second phase that launched the implementation of OHD in NYC. The third and fourth projects are the pilot tests of OHD conducted by the authors in the cities of Bogotá and Sao Paulo. The fifth source of data was a project funded by the Inter-American Development Bank that collected data about the impacts of congestion on supply chains in Latin America. Taken together, the data provide a unique picture of the emissions produced in a sample of important cities in the Americas. This presentation will describe the experiences and chief results obtained from these three projects and the results obtained.

Title: Tackling urban congestion: Federal Highway Administrations' Off- Hours Delivery Grant Program

Author, Affiliation, Country

The FHWA Office of Freight Management and Operations, USDOT-Federal Highway Administration (FHWA), United States of America

Presented By: Tiffany Julien, Transportation Specialist, FHWA

Key Words

Freight Delivery, Urban Freight, Off-hours Delivery

Objectives

The objectives are to:

- Demonstrate and better understand the efficacy of implementing off hours good movement and delivery programs in small to medium size urban areas as related to:
    - Reducing Congestion,
    - Improving Freight Flows,
    - Positively Impacting Air Quality, and Improving Sustainability, Livability and Environmental Justice.
- Research and demonstrate a low cost, easily replicable, operations based on solutions for cities or urban areas with emerging congestion problems.

Background

Agencies at all levels of government are now faced with delivering transportation system performance in a resource constrained environment. Past research has shown that urban transportation systems have excess capacity during off hours, and congestion and lack of capacity during peak hours. Movement or delivery of goods in urban and metropolitan areas is frequently made during peak congested periods, resulting in congestion, inefficient goods delivery, environmental justice issues, increased fuel consumption, higher labor costs and negative air quality impacts. Moving truck deliveries to off hours provides a low cost solution that can reduce congestion, improve freight flows, and have positive impacts on air quality, environmental justice, sustainability and livability of a city or urban area. Recent efforts include the Port of Los Angles and Long Beach marine terminal operators Pier Pass Off Peak program, and the United States Department of Transportation (USDOT) Office of the Assistant Secretary for Research (OST-R) Research and Innovative Technology Administration (RITA) research with Rensselaer Polytechnic Institute for the implementation of this concept in New York City. These projects demonstrated that an off hours program for movement or delivery of goods in an urban area is possible and has notable environmental and transportation benefits.

FHWA Interest in the Program

The Federal Highway Administration (FHWA) Office of Freight Management and Operations (HOFM) in partnership with the Environmental Protection Agency (EPA) and the European Commission are interested in researching and demonstrating the efficacy of implementing off hours goods movement and delivery programs in various environments including sections or specific locations in large metropolitan areas, small to medium size urban , freight facilities, private freight operations and/or supply chains, etc. areas with emerging or growing congestion problems. The nature of the project involves moving trucks to off hours reduce to congestion, improving freight flows, and positive impacts on air quality, environmental justice, sustainability and livability in urban areas. FHWA is specifically looking for new innovative ways to implement this program in order to provide additional options to public stakeholders besides the already successful programs implemented in New York (NY) and California (CA).

Case Studies of Previous Pilot Programs

There are a series of pilot programs that have been implemented in the US and other countries as well, that provide a good perspective of how this program's objectives and incentives can vary based on location. For example, the Concept Inner-City Night Delivery which was implemented in Barcelona and Dublin addresses the delivery during night time with specially equipped low noise vehicles (low noise equipment, Compressed Natural Gas (CNG)) and the allowance for larger trucks to enter the city center which are restricted during the day time. The implementation of Inner-City Night Delivery proved to reduce delays for the logistics service providers by using the free road capacities at night; reduce emissions and energy consumption (less congestion during night time, direct access to the shops); increase logistics efficiencies in terms of the deployment of Heavy Good Vehicles (HGVs) and manpower; and enhances road safety.

The Ports of Los Angeles and Long Beach use the Pier PASS Off Peak program which encourages greater use of container terminals from 6 p.m. to 3 a.m., approximately 40 percent of container cargo traffic shifted to the off-peak during the program's first three years prior to the economic downturn in 2008; recent numbers are closer to 30 percent.

A major pilot study was recently completed in New York City (NYC) and a more formal implementation process is underway in the area under a project funded by the USDOT, and supported by the New York City DOT. The pilot study included an analysis of GPS truck tracking. The analysis indicated that during off-peak deliveries, a truck on a defined route travels an average of 8 mph whereas trucks often average below 3 mph during regular hours. Traffic simulations showed that, with financial incentives to customers to receive off-hours deliveries, trucking companies can garner significant financial benefits in operations. Simultaneously, the number of trucks on the road during peak traffic hours and delivery zone conflicts near large traffic generators can be reduced. During the federally-funded pilot study that ended in January 2010, delivery times dropped an average of 48 minutes, fuel costs were reduced, trucking companies dramatically reduced their monthly parking ticket costs (which are considered a cost of doing business), and several business needs were identified for broader implementation.
http://www.nyc.gov/html/dot/html/motorist/offhoursdelivery.shtml

Surprising facts about deliveries in New York City

Here are just a few of the interesting facts researchers uncovered in the course of planning for the Off-Hour Delivery Project in the Manhattan area of New York City:

- There are 104,463 commercial establishments in Manhattan.
- Every day, those establishments attract 142,822 inbound freight trips and produce 76,766 outbound freight trips.
- Of those commercial establishments, 9,178 are restaurants.
- Every day, those 9,178 restaurants attract 26,779 inbound trips—about three times the amount of freight traffic produced by the Port of New York & New Jersey.
- Switching one receiver from daytime deliveries to off-hour delivery (OHD) between 7 p.m. and 6 a.m. saves eight days of vehicle travel time every year.
- Switching one receiver from daytime deliveries to OHD has the same effect on carbon dioxide reduction as planting two healthy trees per year.
- About 30 percent of all establishments and about 45 percent of restaurants in Manhattan have a vendor they would trust to make unattended OHD.
- For restaurants, having a trusted vendor has the same effect on the decision to shift to OHD as offering a one-time incentive of US $14,483.

[Source: J. Holguín-Veras, et al., "Overall Impacts of Off-Hour Delivery Programs in New York City Metropolitan Area," *Transportation Research Record* (December 2011)]

Previously Awarded FHWA Grants

FHWA has awarded two pilot projects. The two grantees currently implementing this program have proposed innovative cost effective solutions that target freight management operations issues within their respective urban areas.

The first pilot project was awarded to the District Department of Transportation (DDOT) Off-Hours Freight Delivery Program which will focus on improving the management of curbside loading zones in the city by incentivizing businesses to shift to off-hour deliveries. District of Columbia is a dense urban environment with a diverse mixture of land uses that place significant demand on the city's transportation infrastructure. The city's role as an employment center for the region creates a high volume of commuter traffic in peak hours, while the consumer driven economy generates significant demand for freight movement. The District has a constrained infrastructure with multiple modes competing for use of the same space and DDOT believes that a focus on encouraging off-hour deliveries would contribute significantly to reducing congestion.

The second pilot is based on an agreement between Florida Department of Transportation (FDOT) and the Orlando Health Campus. FDOT proposes a pilot project to study the costs and benefits of moving freight deliveries currently occurring during peak traffic time on the Orlando Health campus to the off-hours of the day. The deliverable of this study will be an analysis of the costs and benefits of implementing off-hours freight delivery operations to the facility, carrier, and environment. They will do so by using GPS technology to optimize the delivery time of the carriers which will results not only in social and environmental benefits to the community surrounding this facility but also operational benefits to both the carriers and receivers by optimizing the work hours and resources needed to complete the delivery process.

Smart Urban Logistics Initiative in Austria

Author(s), Affiliation, Country

Patrick Grassl, Federal Ministry for Transport, Innovation and Technology, Austria

Key words

Access to transport networks, infrastructure and nodes; Freight consolidation and transhipment; Implementation of low emission technologies; IT-technologies and solutions; Innovative vehicles, vessels and equipment; ICT, transport optimisation; Communication between authorities: cooperation, procedures, legal frameworks; Communication between businesses and authorities: coordination, consultation, business models

Abstract (1 to 3 pages)

Freight traffic in urban areas forms a complex network of partially independent subsystems and components. Sustainable measures need to be identified, developed and implemented not only on an overall level but also in the individual fields of action. Existing and new instruments are intended to contribute to making logistics and freight traffic in conurbations smarter and more efficient in the future, by a step by step approach.

The Austrian Climate and Energy Fund's annual funding programmes 2013 to 2014 therefore included preparatory work for new subprogrammes under the names "Smart Urban Logistics" and "Efficient Freight Traffic in Areas with High Population Densities." Continuous growth of our cities whilst resources diminish at the same time makes rethinking city planning imperative in the medium term. The constant growth of the cities and the problems caused thereby demand new solutions in urban planning. In this context mobility and traffic are core topics. New and intelligent structures are necessary in order to improve or at least maintain the quality of living.

The aim of the initiative “Smart Urban Logistics” was to build up an Austrian networking platform to boost and promote intelligent solutions in the field of urban logistics. The intention was to make stakeholders aware of the topic, to create acceptance for innovative technologies, to initiate a communication process, to support further discussions and to form an incentive for the start of pilot projects that help to better design cities in the future.

Furthermore it could be experienced in the past that a big number of R&D projects never were continued as practical projects although they were considered to have realistic chances of success. There seemed to be a gap between the first research activities which has to be made to find innovative solutions and the further steps towards the implementation of the solution. This phenomenon regularly marked the end of a promising innovation process.

The “Smart Urban Logistics” initiative was especially aware of that danger and tried to overcome this barrier by sensitising the project partners to that problem, to bring actors together and to promote future-oriented topics that focus on transferable solutions.

The whole initiative has been set-up on a long-term programme for several years and consisted of three phases:

- Phase 1: Development of a strategic roadmap concept and implementation of a stakeholder platform.
- Phase 2: Elaboration of supporting topics in order to evaluate framework conditions and to prepare information for implementation activities:
- Topic 1: Requirement analysis of cities
- Topic 2: Best Practice Toolbox
- Topic 3: Framework conditions and policies
- Topic 4: Management of the stakeholder process
- Phase 3: Set-up of coaching and implementation activities in cities with the goal to initiate pilot projects.

Together with the drawing up of the common strategic roadmap concept a "Smart Urban Logistics Platform" was founded and implemented in order to accompany the initiative. The platform was coordinated by the Climate and Energy Fund, the bmvit (Federal Ministry of Transport, Innovation and Technology), and the Railway Infrastructure Services Company (Schieneninfrastruktur-Dienstleistungsgesellschaft mbH). The success was dependent on the ability of the initiative to integrate the relevant stakeholders into the process:

- Public authorities (ministry, funding, administration, research, etc.)
- Private companies (logistics, forwarders, trade, industry, etc.)
- Associations of cities
- Experts on logistics and traffic planning
- Universities and research institutes

They accompanied the process as members of a steering committee and got information on all the activities of the project in order to spread it within their sphere of influence. Strategic steering meetings were held several times a year and the results and information of the meetings directly influenced the platform, the funding programs of the Austrian government as well as further activities within the initiative. All involved stakeholders helped to disseminate results and to make the initiative well known. "Smart Urban Logistics" was successfully implemented as a national platform and is also recognised as a brand for ideas, networks and coordination of projects dealing with urban logistics.

Within the "Smart Urban Logistics" process a framework of objectives for projects on urban transport has been set up in order to easily evaluate different projects and approaches. According to that best practice projects must reach a reduction of emissions and prevent the waste of resources. Moreover, ecologic, economic and social sustainability has to be considered. The projects must be able to help increase the overall efficiency of the supply of cities with goods and improve the integration of (existing) systems as well as increase the transparency of logistics processes in Smart Cities.

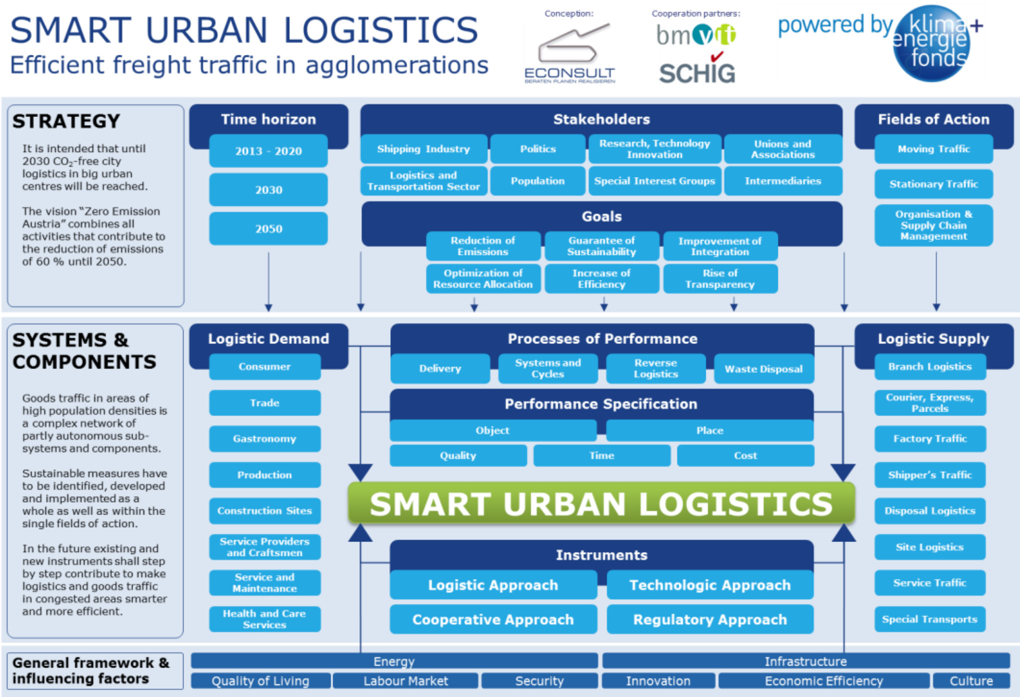
The phase two project prepared three deliverables intended to help Austrian cities successfully implement urban goods movement and logistics projects:

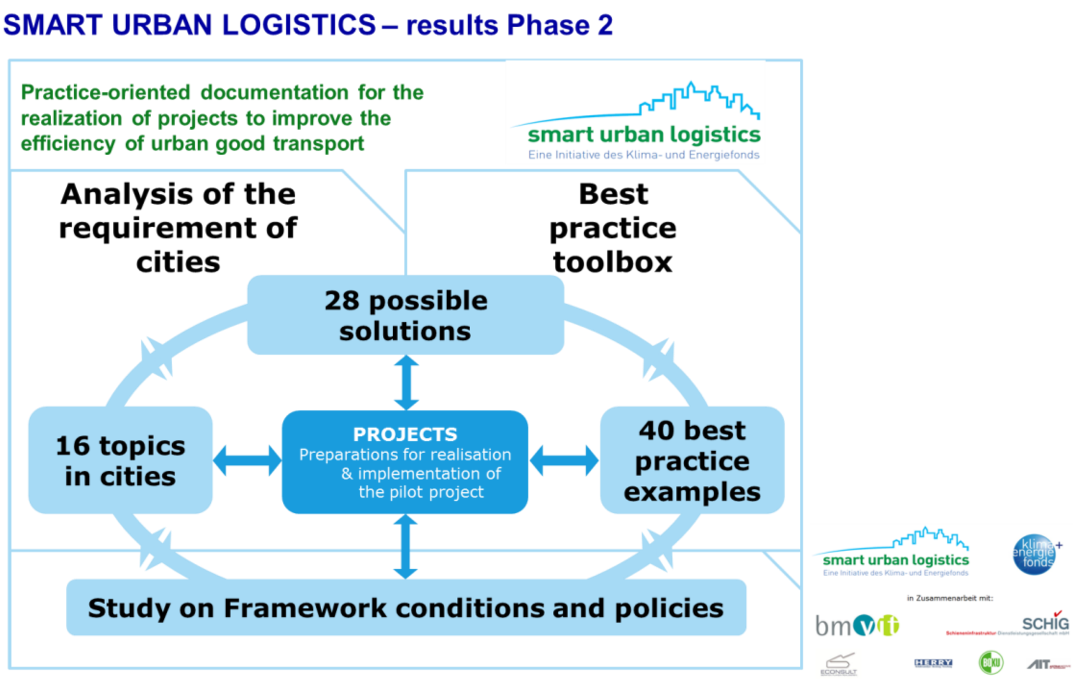
- Handbook on developing urban goods movement and logistics projects.

- Catalogue of national and international urban goods movement and logistics best practice projects.

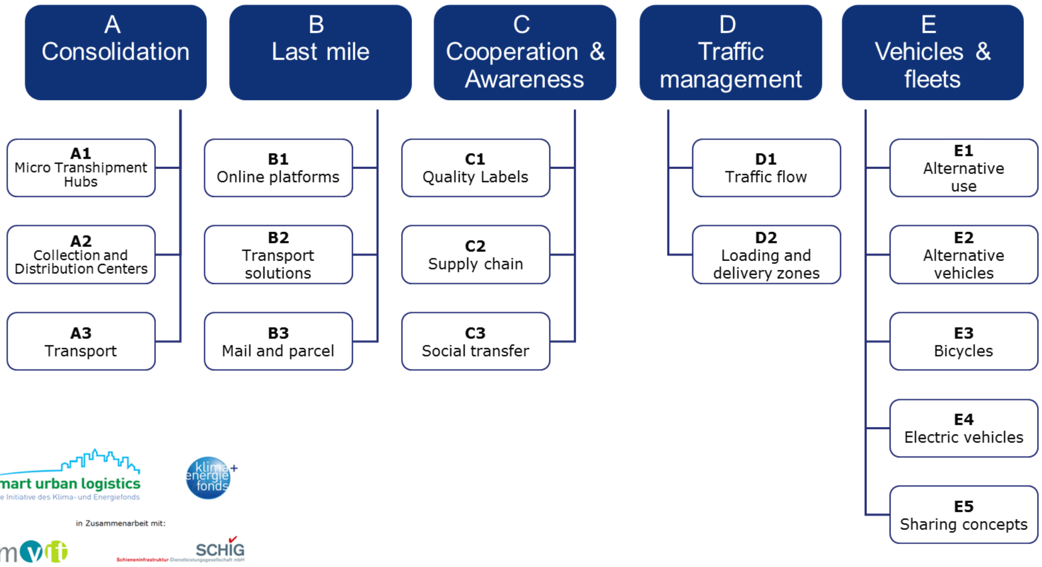
- Overview of legal and regulatory factors affecting urban goods movement and logistics.

Currently the initiative is in the third phase of its operation. A pilot project including a stakeholder process was initiated in an Austrian city in 2015. The stakeholders from the city government used the handbook and supporting materials with their practical recommendations actively for improving communications surrounding urban goods movement and for developing a logistics project, as well as for improving the integration of this project in the city planning process. The catalogue of national and international reference projects helped to support the stakeholders in developing their own project: From then on the focus has been on the implementation of a delivery zone management based on location, time and/or type of goods. Since off-peak hours freight delivery is an interesting option to reduce congestion during business hours, the implementation of deliveries outside normal working hours (like night time deliveries) seems possible. Outcomes of this stakeholder process are expected in the coming year.


SMART URBAN LOGISTICS
Efficient freight traffic in agglomerations
Conception:
ECONSULT
Cooperation partners:
SCHIG
powered by
klima+ energie fonds
STRATEGY
It is intended that until 2030 CO_2-free city logistics in big urban centres will be reached.
The vision "Zero Emission Austria" combines all activities that contribute to the reduction of emissions of 60 % until 2050.
Time horizon
2013 - 2020
2030
2050
Stakeholders
Shipping Industry
Politics
Research, Technology Innovation
Unions and Associations
Logistics and Transportation Sector
Population
Special Interest Groups
Intermediaries
Goals
Reduction of Emissions
Guarantee of Sustainability
Improvement of Integration
Optimization of Resource Allocation
Increase of Efficiency
Rise of Transparency
Fields of Action
Moving Traffic
Stationary Traffic
Organisation & Supply Chain Management
SYSTEMS & COMPONENTS
Goods traffic in areas of high population densities is a complex network of partly autonomous sub-systems and components.
Sustainable measures have to be identified, developed and implemented as a whole as well as within the single fields of action.
In the future existing and new instruments shall step by step contribute to make logistics and goods traffic in congested areas smarter and more efficient.
Logistic Demand
Consumer
Trade
Gastronomy
Production
Construction Sites
Service Providers and Craftsmen
Service and Maintenance
Health and Care Services
Processes of Performance
Delivery
Systems and Cycles
Reverse Logistics
Waste Disposal
Performance Specification
Object
Place
Quality
Time
Cost
SMART URBAN LOGISTICS
Instruments
Logistic Approach
Technologic Approach
Cooperative Approach
Regulatory Approach
Logistic Supply
Branch Logistics
Courier, Express, Parcels
Factory Traffic
Shipper's Traffic
Disposal Logistics
Site Logistics
Service Traffic
Special Transports
General framework & influencing factors
Energy
Infrastructure
Quality of Living
Labour Market
Security
Innovation
Economic Efficiency
Culture


SMART URBAN LOGISTICS – results Phase 2
Practice-oriented documentation for the realization of projects to improve the efficiency of urban good transport
smart urban logistics
Eine Initiative des Klima- und Energiefonds
Analysis of the requirement of cities
Best practice toolbox
28 possible solutions
16 topics in cities
PROJECTS
Preparations for realisation & implementation of the pilot project
40 best practice examples
Study on Framework conditions and policies
smart urban logistics
in Zusammenarbeit mit:
SCHIG

Smart Urban Logistics - Best Practice categories and cluster



smart urban logistics
Eine Initiative des Klima- und Energiefonds
in Zusammenarbeit mit:

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Session 5 : Heavy Vehicle Impact on Infrastructures

Chair: Bernard Jacob (IFSTTAR, France)

Impacts of heavy vehicles on roads – New research developments

Jean-Michel Simonin, Pierre Hornych, IFSTTAR, France

Economical development leads to increase of transport of heavy goods in many countries, and poses the question of optimizing vehicle loads, to minimise impact of this transport on pavements. Classically, pavement design methods are based on linear elastic calculations, and the impact of heavy vehicles is mainly evaluated in terms of fatigue of the road base layers. However, heavy vehicles also lead to other deterioration mechanisms, such as rutting and wear of surface courses (wear, raveling, top down cracking), which are still not well taken into account in pavement design.

After presenting the standard design approach for evaluating pavement fatigue, some recent research developments, on the response of bituminous pavements to vehicle loads are presented.

The first results concern the importance of weight in motion (WIM) data for the evaluation of traffic aggressiveness. Usually, in the French pavement design method, as in many other methods, heavy traffic is converted into an equivalent number NE of standard axle loads (or ESALS) which are then used for pavement calculations. In the French pavement design method, this number of equivalent axle loads is determined using a Coefficient of Aggressiveness (CA) of the traffic, which allows to convert the number of heavy vehicles N_{HV} into a number NE of standard axle loads : NE = CA x N_{HV}.(figure 1). In most cases, the values of the Coefficient of Aggressiveness CA used for pavement design are empirical, and are only related to the level of traffic (Daily average traffic), and not to the real vehicle loads. However, using WIM data, a real value of Coefficient of Aggressiveness CA , based on real distributions of the axle loads of the vehicles can be calculated. Such calculations performed for several WIM stations, have shown that the real values of CA can differ significantly from the empirical values generally adopted for design, and can lead to significant differences in pavement design lives.

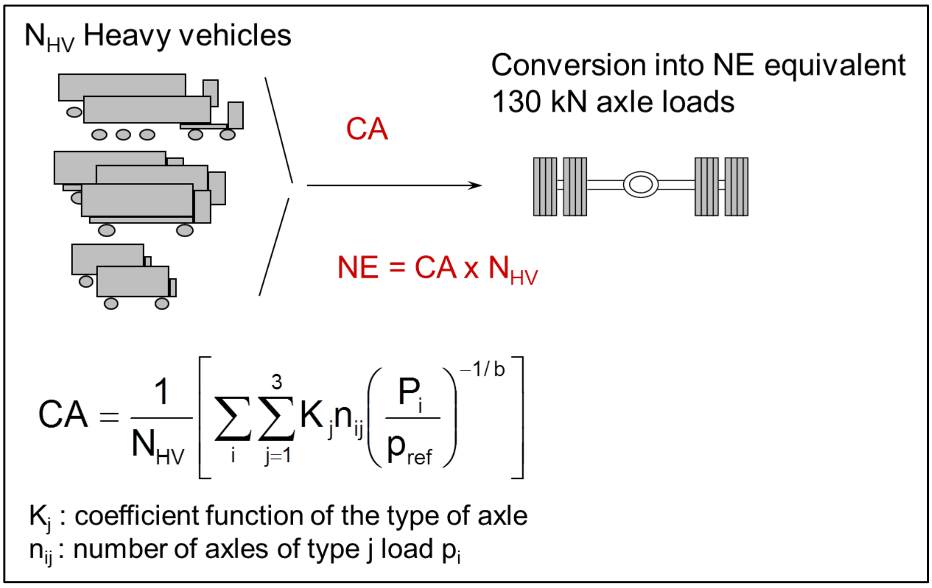


Figure 1 : Definition of a coefficient of aggressiveness CA, converting the traffic into a number NE of standard axle loads.

The second development concerns the modelling of the viscoelastic behaviour of bituminous pavements. Bituminous materials present a thermos-viscoelastic behaviour, which leads to a large variations of their modulus with loading frequency and temperature, and to the accumulation of permanent strains under loading. In France, a new pavement modbelling software, called Viscoroute, taking into account the visco-elastic behaviour of bituminous layers has been developed . This software is based on the Huet-Sayegh viscoelastic model. Many comparisons with full scale accelerated tests and measurements on instrumented pavements have been performed, and have shown that the visco-elastic model gives much more realistic predictions of pavement response than linear elastic model. Viscoroute is particularly suitable for modelling pavement response to aggressive loading conditions, such as high temperatures at slow loading speeds, or multiple axle loads.

Recent research (Homsi, 2011) has also focused on the development of an improved fatigue law for bituminous materials, taking better into account real stress-strain variations under multiple axle loads (see figure 2).

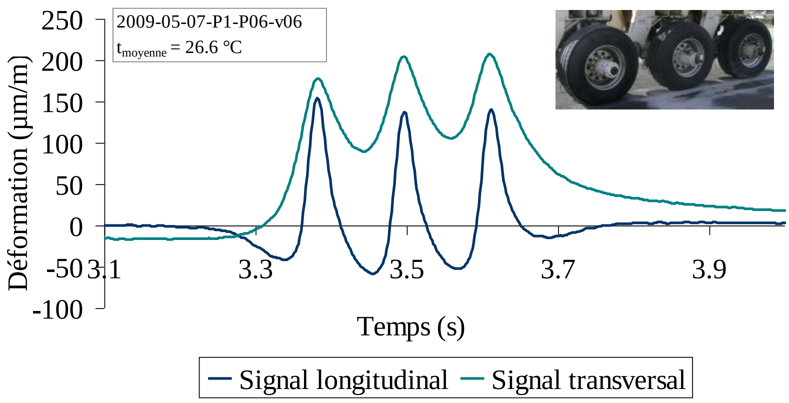


Figure 2 : typical longitudinal and transversal strain signals at the bottom of the bituminous base layer, under tridem axle loading.

This research was based on laboratory fatigue tests, simulating real multiple axle load signals. From this study, it was possible to propose a new “extended” fatigue law, taking into account 4 independent parameters related with the shape of the load signal (see figure 3). An example of expression of this fatigue law is presented on figure 4. This new fatigue law has been applied, since, to evaluate the impact on pavement fatigue of different heavy vehicle configurations such as the new EMS (European modular System) vehicles used in some European countries, with increased load capacities (up to 60 T , with 8 axles..).

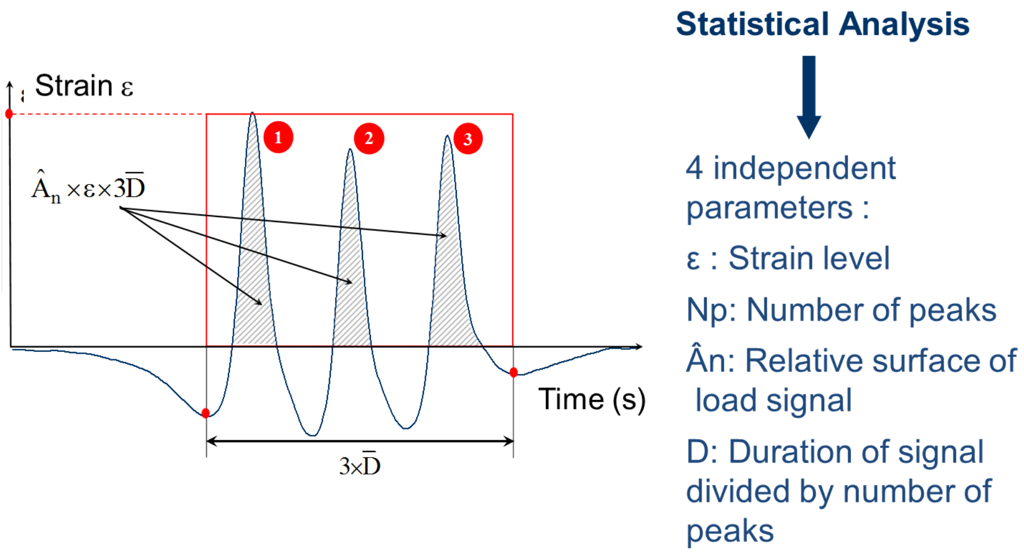
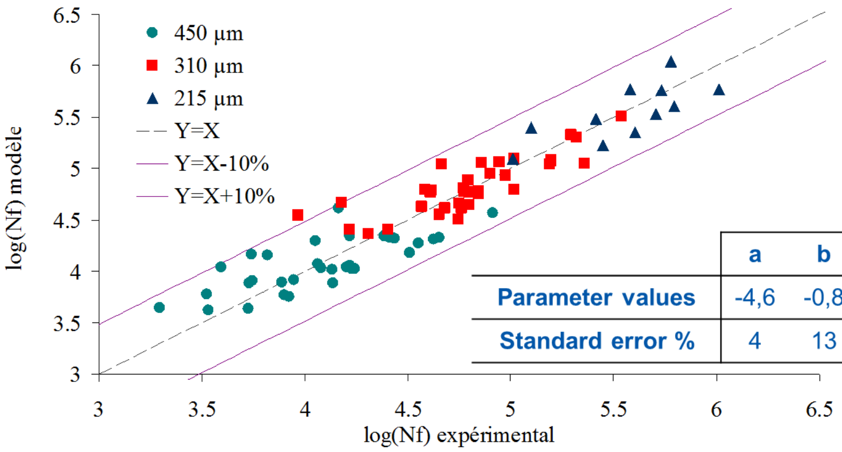


Figure 3 : independent parameters proposed to describe the multiple wheel load signal

$$\log(Nf) = a \log \boxed{\varepsilon} + b \log(\boxed{Np}) + c \boxed{\hat{A}n} + d \boxed{D} + e \qquad \text{Correlation } R = 0{,}91$$



	a	b	c	d	e
Parameter values	-4,6	-0,8	1,3	1,8	15,2
Standard error %	4	13	15	17	3

Figure 4 : proposed multilinear fatigue model and example of application.

The last part of the paper presents some research dealing with the effect of heavy vehicle loads on surface courses, and wheel-pavement interaction. To simulate deterioration of surface courses, a new test equipment, called Triboroute has been developed at IFSTTAR, to evaluate the resistance to ravelling of bituminous materials. This test simulates the effect of rolling wheel loads, with controlled horizontal forces, on the pavement surface (see figure 5), and the resistance to ravelling is measured by the loss of material observed in function of the number of applied load cycles. This test represents a new means of measuring the resistance of wearing course materials to horizontal loads, in particular in specific areas like slopes, braking areas, roundabouts, and will allow to develop suitable performance criteria for resistance to ravelling of bituminous materials.

Figure 4 : Triboroute: Laboratory test equipment to simulate deterioration of surface course

To understand the deterioration mechanisms of surface courses, research has also been conducted on the IFSTTAR accelerated testing facility, to measure strain fields generated in surface pavement layers by different tire loads (wide-based single tires or dual tires). For this purpose, a new type of optic-fiber sensors, developed by Laval University and OPSENSE have been used. These sensors consist of a plate, equipped with numerous small fiber optic sensors, placed horizontally and vertically. This plate is inserted in the pavement, and allows to measure accurately the strain field in the upper pavement layer, under wheel loading (figure 6). This measurement technique has led to a better understanding of the complex, tri-dimensional, strain fields to which upper pavement layers are submitted, and consequently to the damage mechanisms of these layers.

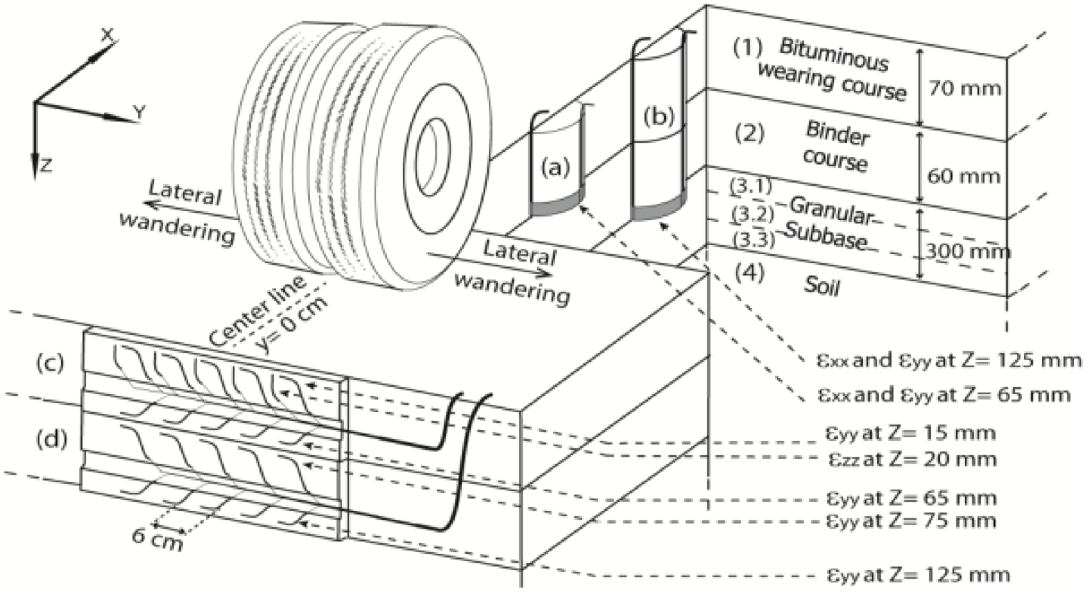


Figure 5 : Optical fiber system for measurement of strain fields under wheel loads

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