ICWIM8

8th International Conference on Weigh-in-Motion

Editors : Bernard Jacob & Franziska Schmidt

Prague, May 19-23, 2019

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Preface

The 8th International Conference on Weigh-In-Motion (ICWIM8) comes back to Europe, after two editions in North and Latin America. It is the first ICWIM organized in Central (former Eastern) Europe. The local organization is subcontracted to the Czech Transport Research Centre (Centrum Dopravniho Vyzkumu, CDV). 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) organizing a successful conference and leading the International Scientific Committee (ISC). Three International organizations are also partners of this conference: the International Transport Forum of the OECD (ITF), the World Road Association (PIARC) and the Forum of European Highway Research Laboratories (FEHRL).

ICWIM has a rich history, with a series of 8 conferences held in 4 continents: Zürich (1995), Lisbon (1998), Orlando (2002), Taipei (2005), Paris (2008), Dallas (2012), Foz do Iguaçu (2016) and now Prague (2019). 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 (2016) was combined with a PIARC International seminar.

ICWIM8 is held as a series of 8 dedicated sessions with fully peer reviewed papers published in these proceedings, and two panel discussions. ICWIM8 also includes for the first time an end-user series of sessions specifically designed for practitioners to be exposed to the benefits, uses and value that mass data brings.

The conference addresses the broad range of topics related to on-road and in-vehicle WIM technology, its research, installation and operation and use of mass data across variable end-uses. Innovative technologies and experiences of WIM system implementation are presented. Application of WIM data to infrastructure, mainly bridges and pavements, is among the main topics. However, the most demanding application is now WIM for enforcement, and the greatest challenge is WIM for direct enforcement. Most of the countries and road authorities should ensure a full compliance of heavy vehicle weights and dimensions with the current regulations. Another challenging objective is to extend the lifetimes of existing road assets, despite of increasing heavy vehicle loads and flow, and without compromising with the structural safety. Fair competition and road charging also require accurately monitoring commercial vehicle weights by WIM.

WIM contributes to a global ITS (Intelligent Transport System) providing useful data on heavy good vehicles to implement Performance Based Standards (PBS) and Intelligent Access Programme (IAP, Australia) or Smart Infrastructure Access Programme (SIAP).

The conference reports the latest research and developments since the last conference in 2016, from all around the World. More than 150 delegates from 33 countries and all continents are attending ICWIM8, mixing academics, end users, decision makers and WIM vendors. An industrial exhibition is organized jointly with the conference.

We greatly appreciate the support of the major sponsors of the conference: Camea, Cross, Intercomp, International Road Dynamics (IRD), Kistler AG, Q-Free and Vanjee.

Bernard Jacob
Vice-president Science of ISWIM
International Scientific Committee Chair
IFSTTAR, France

Franziska Schmidt
International Scientific Committee Vice-chair
IFSTTAR, France

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 – both on-road and in-vehicle. It supports advances in WIM technologies and promotes more widespread use of WIM and its widespread applications including the use and benefits of mass information.

ISWIM brings together three distinctive groups:

- users
- researchers, and
- vendors of systems for weighing of vehicles in motion.

Organizing WIM conferences and seminars is one major objective. ISWIM has successfully held seven International Conferences on Weigh-in-Motion (namely ICWIM 1 to 7) including Zurich, Lisbon, Orlando, Taipei, Paris, Dallas and Foz-do-Iguazu. In addition, International Seminars have been organized, such as in Florianopolis (Santa Catarina, Brazil) in 2011. Furthermore, ISWIM actively participates in sister organization events including (for 2018 only):

- Intertraffic (20-23 March 2018), Amsterdam, Holland. The workshop on the uses of WIM for Enforcement was held
- NATMEC, a short presentation on ISWIM at the plenary opening session and a 1-hour ISWIM session
- SATC, Southern African Transport Conference and Exhibition (9-12 July 2018), a full day ISWIM workshop was held
- HVTT (2 – 5 October 2018), Rotterdam, Holland. The seminar included a 50-minute ISWIM side event

As part of the outreach program, ISWIM publishes on a quarterly basis the ISWIM Newsletter. The newsletter covers stories from the WIM world including articles from users, academics and vendors.

ISWIM is also active on the Internet through its web site http://www.is-wim.org and is actively involved though its LinkedIn account. The social media offers an International portal for all things WIM, with many resources, such as scientific and technical publications, links to WIM web sites, and facilitates exchanges of WIM experiences. The website 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. There is no membership fee for individuals. There is a membership fee for companies and organizations.

ISWIM has widespread individual membership from 73 countries.

The Vendors College consists of 19 members from 13 different countries who all are actively involved in the manufacture and supply of WIM equipment globally. The Vendors College has grown over the years, and still continues to do so, since ISWIM was first formed and is proud to have an active and leading role within the society. The members of the college meet from time to time between the international ICWIM conferences, usually at trade fairs, where members are likely to be attending to discuss pertinent matters relevant to their interests. In addition, the members of the college vote for a presence on the ISWIM board, where they are represented by two of their elected members.”. There is a Board of up to 15 members which is elected by the General Assembly of all members.

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**.

Chris Koniditsiotis
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Panel Discussions

Panel Discussion 1

WIM for direct enforcement

Chair: Bernard Jacob (IFSTTAR, France)
Adriana Antofie (BE), Victor Dolcemascolo (FR), MiklosToldi (HU), Jonathan Regehr (CND), Gerard Schipper (ECR)

Panel Discussion 2

WIM data quality for applications

Chair: Chris Koniditsiotis (TCA, Australia)
Jens Dierke (DE), Miles Le Roux (SA), Chul-Woo Kim (JP), Lily Poulikakos (CH), Olga Selezneva (US), Valter Tani (BR)

Session 1 : End-users Experience with WIM

Chair: Jonathan Regehr (University of Manitoba, Canada)

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. Some statistical results about overloadings are shown. Finally, we present the results obtained with the phase 1 of the national project called 'direct enforcement of overloading by WIM' and the work planned in phase 2.

Keywords **:** Heavy vehicles, light commercial vehicle, 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. Des résultats statistiques sur le contrôle des surcharges sont présentés. Enfin, nous présenterons les résultats obtenus sur la phase 1 du projet CSA surcharge, pour lequel le ministère français en charge des transports est maître d'ouvrage et le travail prévu en phase 2.

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, Transport 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 coaches for intercity passenger transport. 84.9% (in ton-kilometers) 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 about 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 maximum axles load of the tractor or the semi trailer at 12 tons 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 download 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 resources

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 tasks is to fine trucks overloadings.

3.2 High speed weigh in motion

In 2004, the Minister of Transport announced 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 1). 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. 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.

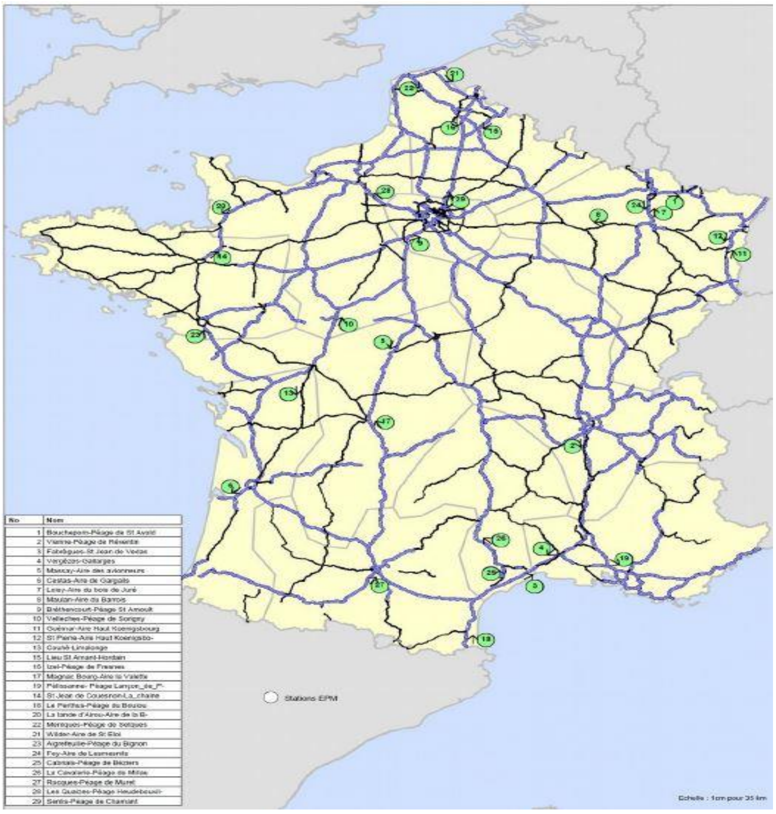

Figure 1 – The HS WIM sites network

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 2);

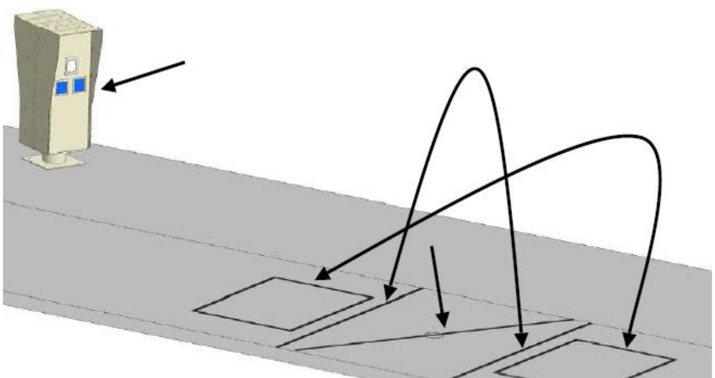

Figure 2 – Image of a suspected overloaded truck

- 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.

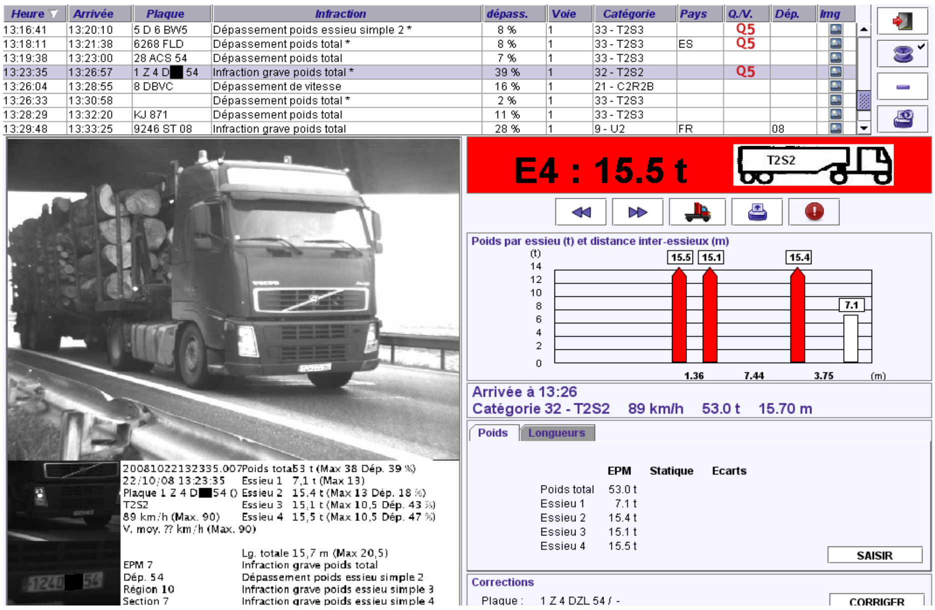

Figure 3 – Image of a suspected overloaded truck

Yearly, the characteristics (axle loads, speed, silhouette, axle spacing, total vehicle length) of 120 millions of vehicles, including 30 millions of trucks, are recorded by the HS WIM french network.

4. How are used the HS WIM Data

4.1 Statistical results

4.1.1 Performance of the pre selection of overloaded trucks

In order to estimate the performance, of the pre selection using HS WIM, it was decided to compare, for 18 WIM sites, the number of truck seen as overloaded by the HS WIM system and the number of trucks detected as overloaded using static devices.

Table 1 – Efficiency of HS WIM used for pre selection

Number of trucks both weight in static and in motion	Number of pre selected trucks as seen as overloaded by HS WIM	Number of overloaded trucks (confirmed by static weigh measurements)
407	300	256
	efficiency	85,00 %

The efficiency of HSWIM technology for the pre selection is 85%.
Without pre selection device and according to the control officers, when 3 trucks are stopped by the control officer, only one is really overloaded. The use of an HSWIM system lead to increase the pre selection efficiency by about a factor 3, which is very important.
Thanks to this performance, the system is well appreciated by the control officers and is considered as a powerful tool. This level of performance is very high, so that the controller officers trusts the system and uses it.
Thanks to this result, only the overloaded trucks are controlled. There is no waste of time both for the control officers and the transport companies which respects the legal weights.

4.1.2 HS WIM Statistics

- Number of trucks recorded by the HSWIM network (Hombourger and al, 2019)

In 2017, at about 30 millions of trucks were recorded by the French HSWIM

- Main silhouette

Most truck traffic consists of 2-axle tractor with a 3-axle semi-trailer (70,0%), followed by 2-axle tractors and 2-axle semi-trailer (12,0%), 2-axle trucks (6%). The other categories represent less than 5 % of heavy truck traffic.

- Level of overloading

In 2017, at about 7 % of the truck traffic flow is overloaded on the gross weight.
9 % of the 2-axle tractor with a 3-axle semi-trailer were overloaded on the gross weight, and less to 1% for the 2-axle tractors and the 2-axle semi-trailer and the other vehicles.

4.2 Use of HS WIM system

4.2.1 Differed time

- For targeting the most offending companies (Jacob and al, 2002)

In order to improve the efficiency of the static control, WIM data files are processed for each site in order to determinate the most overloaded trucks.

Since the identification plates are recorded by the HSWIM system and using the national registration file, it is possible to identify the transport company which belong the truck. Monthly, this work is performed and the control agent is able to target the most offending companies. Thus, officers choose the companies they plan to inspect in the headquarter of the transport company. It is possible for instance to check the driving and resting time of all the drivers on a 26 days period, as these data are recorded in the headquarters of the transport company.

-For targeting the most overloaded WIM site

HSWIM system are able to record all the data from the traffic flow (gross weight, axle weight, vehicle silhouette, lateral position in the lane, vehicle speed and length, axle spacing, …) during all day and hour of the year. Thanks to theses records, statistical data processing of the WIM data lead to determinate :

- where are the most overloaded WIM sites;
- and for which days of the week and which hours, static controls sessions have to be planed.

Table 2 - Statistics for one week on overloaded trucks numbers

Day	Number of truck	Number overloaded trucks	Percentage of number of overloaded trucks
Thursday	**2038**	314	15,4
Wednesday	**2033**	307	15,1
Monday	**1997**	283	15,4
Tuesday	**1831**	281	14,1
Friday	**1761**	258	14,6
Saturday	**732**	119	16,3
Sunday	**236**	46	19,4

Table 2 shows the number of overloaded trucks depending on the day of the week, for a given site.

For efficiency reason, it is better to perform overloading controls on Thursday, because for this day of the week, there are the maximum of overloaded trucks.

Wednesday can also be chosen as a suitable day in order to plan overloading controls.

4.2.2 Real time

Figure 3 shows a photo of a suspected trucks detected as overloaded by the HS WIM system. This photos shows the silhouette of the truck, its color, the identification place and the criteria of overloading : the single axle of the tractor and the two axles of the tandem of the semi trailer are overloaded. Thanks to this photo, the police is able to pick up the suspicious vehicle from the traffic in order to control it with static weighing device. The level of fine is calculated after these static measurements.

5. Toward a direct enforcement WIM system

Direct enforcement of overloadings of heavy good truck, but also light commercial vehicle, is one solution for making more dissuasive 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 obtain an 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 2014-17 to demonstrate the feasibility of type approval by OIML a HS-WIM system for direct enforcement;

(2) phase 2 in 2018-19 is to design a method for type approval in order to use WIM for direct enforcement of overloadings. It aims also to i

Phase 1 of the project has demonstrated that the feasibility of using WIM technology for direct enforcement of overloadings can be reached, if an appropriate sorting algorithm.

5.1 Main finding of phase 1 of the project

Phase 1 (2014-17) of the direct enforcement WIM project (Cottineau and al, 2017) has demonstrated the feasibility of automated direct enforcement of overloaded truck and that current WIM systems could respond to them, with the implementation of suitable algorithms and sorting criteria.
The results of phase 1 are :
- a characterization of the response of the piezo-ceramic and quartz load sensors on a test bench in the laboratory and on the IFSTTAR circular accelerated testing facility in Nantes;
Piezo-quartz (Kistler) sensors are the most suitable for direct enforcement of overloadings because of their lower sensitivity to external factors;
- Testing on the Saint-Avold site (A4 motorway, SANEF), which lead to collect WIM data from more than 1,000 heavy good vehicles and the corresponding static reference weights, show that the OIML 5 class is reached for a significant part of the measurements using 3 or 4 sensor lines and for the 2-axle tractor with a 3-axle semi-trailer vehicles which are loaded closely to their legal limit gross weight ;

- Phase 1 also enabled IFSTTAR and Cerema to develop methods of sorting based on the data collected on the IFSTTAR circular accelerated testing facility and on the Saint-Avold site. The sorting method has been tested on a few hundred trucks and the results obtained are encouraging. The robustness will be confirmed by the continuation of WIM data collection.

5.2 Objective of phase 2

It remains in phase 2 to establish a of approval of model procedure (homologation) in accordance with the OIML recommendation R-134 (OIML, 2006). The goal is to meet the requirements of OIML5 (at least for the gross weights and the heaviest trucks).

A working group had been set up to prepare the homologation with the French national authority, the French ministry of transport, IFSTTAR and Cerema.
Manufacturers can then apply for approval of their system in the accuracy class suitable with the enforcement needed class.
It will be necessary to check that a different class can be selected for the light commercial vehicle, because the relative error for these vehicles will not be able to respect the tolerance of ± 5% OIML accuracy class.
To be integrated into the automated sanction chain, the Directorate of Road Safety (DSR) requests that the false positive rate is lower than 1% (risk of wrong verbalization). Phase 2 research work is in progress.

6. 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 dissuasive the overloading for all the traffic truck.

That is why, the success of the French direct enforcement project is crucial for the French Ministry of Transport.

It is crucial to enforce heavy good vehicle but also light commercial vehicle (LCV), because studies have found that LCV used for international transport generates unfair heavy good vehicle transports and a negative impact on climate. As the payload of a LCV is about 20 less important than the payload of the 2-axle tractor with a 3-axle semi-trailer vehicles, 20 LCV will circulate instead of one 2-axle tractor with a 3-axle semi-trailer vehicles.

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USE OF THE FRENCH WIM EQUIPMENT DATABASE



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Abstract
Weigh in Motion systems (WIM System) have been deployed in France alongside roads and highways at strategic points on the road network since 2006 to carry out an automated screening of overloaded road transport vehicles. App. one million of trucks are recorded every year on each WIM site, which in total represents thirty millions of weightings. Such a rich database is used for targeted local or national studies, mainly for public purposes, especially for the French Ministry in charge of Transport and his scientific and technical network, but sometime in some public-private partnerships. Some examples of uses of the database are presented in this paper.

Keywords: Weigh-in-Motion, WIM, WIM equipment database, Heavy vehicles, Freight transport, Enforcement, Heavy traffic evolution and studies, user's perspectives

Résumé
Les systèmes de pesage en marche ont été déployés en France sur des routes et autoroutes à des points stratégiques du réseau routier depuis 2006 afin de procéder à un contrôle automatisé des véhicules de transport routier en surcharge. Près d'un million de poids lourds sont enregistrés sur chaque équipement de pesage en marche, ce qui représente au total 30 millions de pesées. Une base de données aussi riche est utilisée pour des études locales ou nationales ciblées, principalement à des fins publiques, notamment pour le Ministère des Transports français et son réseau scientifique et technique, mais parfois dans le cadre de partenariats public-privé. Quelques exemples d'utilisation de la base de données sont présentés dans ce papier.

Mots-clés: Système de pesage en marche, SPM, base de données des SPM, Poids lourds, transport de marchandises, contrôle, Evolution et études du trafic poids lourd, perspectives de l'utilisateur

1 Introduction

Weigh in Motion systems (WIM System) have been deployed in France since 2006 to carry out an automated screening of overloaded road transport vehicles. That contributes improving the safety of road users, preserving infrastructure, ensuring compliance with competition rules between companies and working conditions for road drivers. Marchadour and Jacob have presented the development and implementation of a WIM network for enforcement in France (2008).

29 WIM systems are deployed alongside roads and highways at strategic points on the French main road network (borders, seaports, etc.). These WIM systems also provide a very large database of data, which is used by the Ministry of Transport and some French research and consulting public institutes. However, these data could be even more used if the open data rules could be applied.

Each WIM system measures several parameters, e.g. gross vehicle weight, axles loads, vehicle categories, lateral position in the lane, vehicle speed and length, axle spacing, etc., for all heavy commercial vehicles, without slowing down or diverting them from their way. All informations are recorded 24/24, 7 days a week and make it possible to build a valuable database for the knowledge of the road traffic of heavy vehicles. It is currently the only system that allows to acquire such a dataset. Furthermore, for all measurements 5% or more above the legal threshold (gross weight, axle load or speed), a picture of the vehicle and its plate number is taken and stored for a maximum period of one month. Stanczyk, Geroudet, Thiounn and Millot have described equipments, the WIM sensors, the data collected and data processing software, and the first results of the prototype system (2008).

2 Recurrent use of the WIM equipment database

2.1 Overload detection and statistics

2.1.1 Accuracy of the WIM systems

Cerema assists the French Ministry of Transport in deploying and managing the operation of the WIM system network and carries out studies on the evolution of this network. These systems are used mainly for overload preselection prior to a check point equipped with approved scales during the enforcement sessions. This point is presented by Dolcemascolo and Jacob (2018), but it can be mentioned here that the WIM equipment database allows either to focus the checks on the relevant times and locations. Each WIM equipment is at least class C (15) accuracy, as defined in the document “COST 323: Weigh-in-Motion of Road Vehicles”, the final report (1993-1998).
The tolerance of the class C (15) is presented in this table.

Table 1 – Confidence interval width for the class C (15)

Criteria (type of measurement)	Confidence interval width (%)
Gross weight	15
Axle load :	
- Group of axles	18
- Single axle	20
- Axle of a group	25

In practice, the accuracies of WIM equipment are generally in class B (10). To obtain this accuracy, signal processing algorithms have been developed to improve accuracy. At present the algorithm takes into account the position of the vehicles and this makes it possible to reinforce the precision class B (10). The automatic calibration of the sensors is very efficient. Without human intervention, the system whatever the period of the year gives the same precisions.

2.1.2 National statistics about the heavy traffic

The WIM equipment database makes it possible to produce the key figures of heavy traffic on the national road network and highways. Heavy traffic is mainly represented by 2-axle tractor-type vehicles with 3-axle semitrailers (T2S3) either on the national road network or on the network of motorway concession companies. This traffic is estimated at 68.1% of all heavy traffic on average between 2012 and 2016.

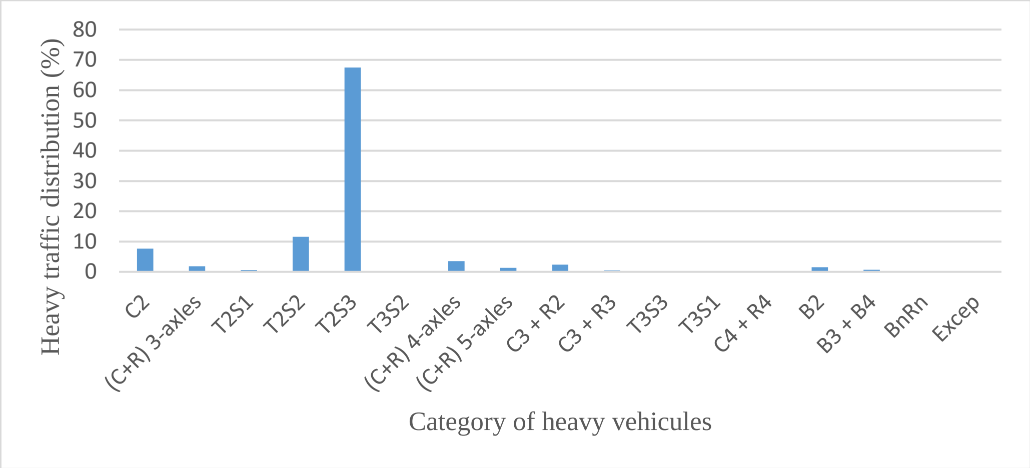

Figure 1 - General composition of heavy traffic on average between 2012 and 2016

The most representative vehicles, T2S3 and T2S2, have an average weight of 29,5T and 20,9T respectively between 2012 and 2016. Average weights of each category have not evaluated a lot.

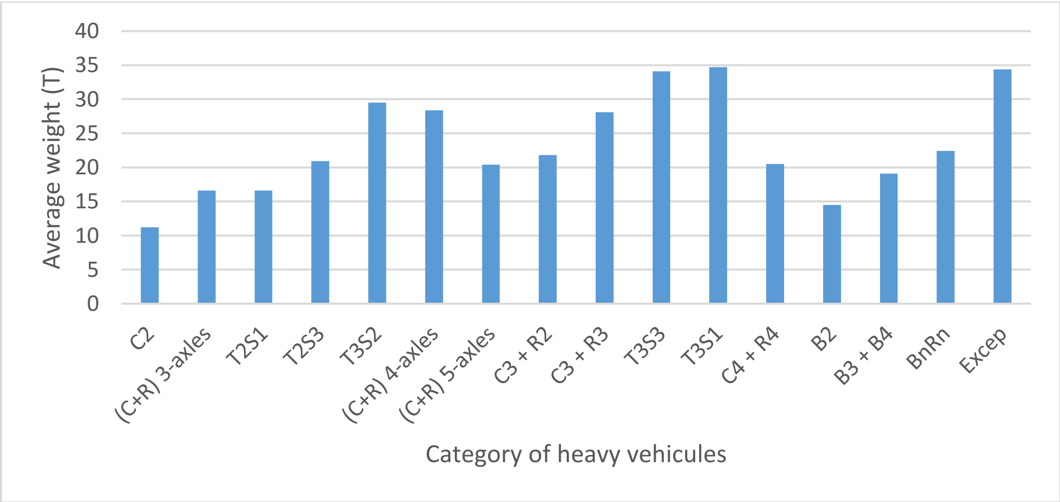

Figure 2 – Average weight by category of heavy vehicles between 2012 and 2016

The average speed of each category is constant, has changed just a little bit in recent years. It is located under the authorized speed limit, whether the vehicles are dedicated to passengers transport or freight transport. Bus run at around 94 km/h (speed limit allowed 100km/h) and the other heavy vehicles have an average speed around 84km/h (speed limit allowed 90km/h).

Average vehicle lengths have not changed so much in recent years. The average observed evolution is around 1 meter for all heavy vehicles. For categories of vehicles that are most representative of heavy traffic, this evolution is very small. T2S3 have an average length of 16,5m and its evolution in 5 years is less than 0,1m.

2.1.3 National statistics about overloads

The overweight rates for heavy vehicles by total weight can range from 0.5% to 6.50% in 2017. This rate depends on several parameters, including heavy vehicle traffic observed on the WIM equipment and its location.

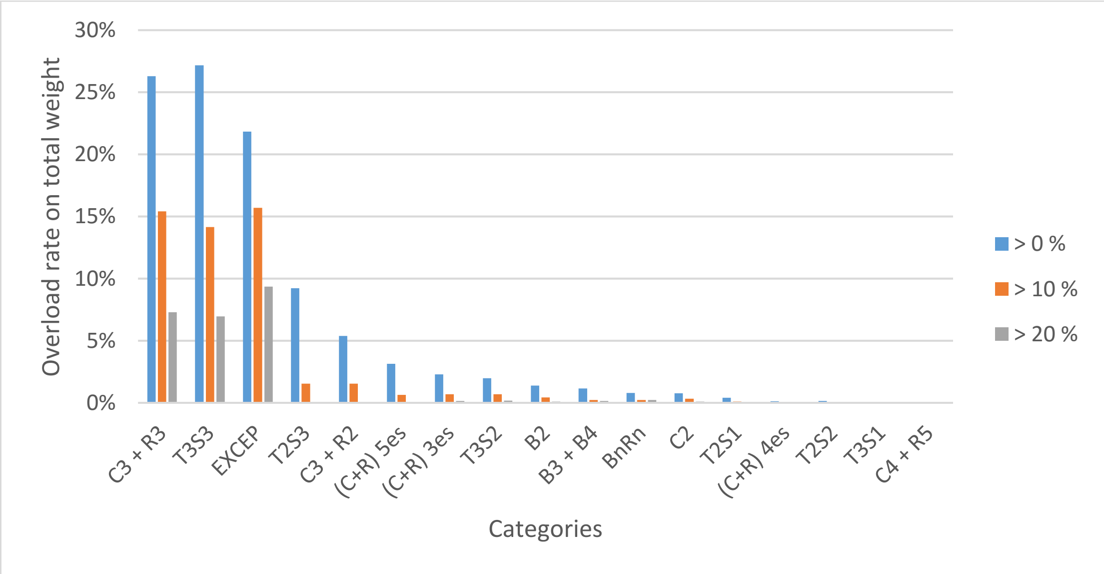

Figure 3 – Overload rate on total weight by category

As shown in the figure 3, vehicles with more than 5 axles have significant overload rates. Among these vehicles, a number has a derogation, but the WIM equipment can not do the sorting! Vehicles with 6 axles exceed by more than 20% the load threshold of 40 t. In 2017, 8.5% of heavy vehicles are overloaded in relation to the total weight allowed, 1.3% exceed it by more than 10% and 0.1% by more than 20%.

The following figure shows the overload rate on simple axle weight (the allowed threshold is 13 t). Trucks with trailers (C + R) 5 axles have the greatest number of overloads on single axles. 1% of the axles exceed the threshold of 13 t allowed, 0.26% exceeds it by more than 10% and 0.06% by more than 20%.

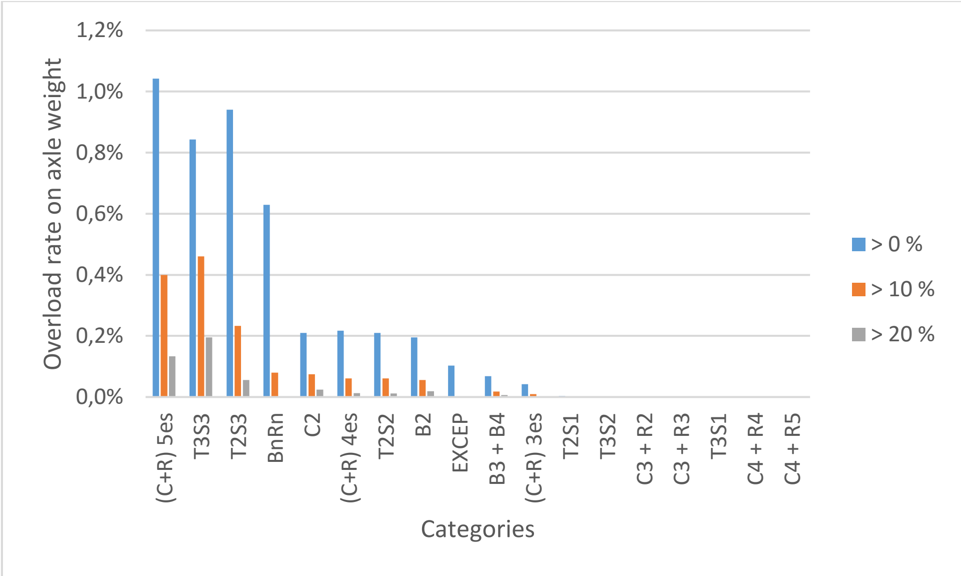

Figure 4 – Overload rate on axle weight by category

2.2 Requisition for police services

The police services, it can be the regional judicial police service, the national gendarmerie or the national police, can request Cerema to make requisitions on the WIM equipment database.

Police services may request to check if the registration of a vehicle has been recorded on one of the WIM equipment or request the registration of all vehicles passed in front of a WIM equipment in a certain direction of circulation, over a defined period of time. If the vehicle is past in front of the WIM equipment, Cerema provides all the information it has on this vehicle. It can be a light vehicle or a vehicle of a particular nationality or a heavy vehicle. Around twenty requisitions are registered annually, but some requirements are impossible to achieve, because they are not enough precise, they are not adapted to the software associated to the WIM equipment or the WIM equipment concerned was not in working order.

These requisitions of the police services can be used in search of stolen vehicles, for the narcotics brigade or others motivations. Cerema doesn't know reason for these requisitions, only if it is indicated in the request and some information are too much sensitive to be published.

3 Specific use of the WIM equipment database

3.1 Traffic evolution after the governmental decree allowing 44t

In 2014, the government asked the General Council for the Environment and Sustainable Development (CGEDD) to supervise a study to evaluate the stakes and the impacts of the transition from 40 to 44 tons of the permissible total weight (Aubreby and Fedou, 2014).

The analysis of the traffic in this report was essentially based on the measurements collected by the WIM equipment. Of all the traffic data collection devices available in France, these stations are the only ones capable of reliably and with a sufficient accuracy of measurements of flow rates, classification by categories or silhouettes as well as measurements of axle load and of total weight.

This last point is essential, because the parameter to be taken into account to evaluate the impact of the heavy vehicle on the roadway is not its total weight, but the weight of each of its axles. We can not be satisfied with an average per axle: the agressivity is calculated using the number of axles, the average axle load and gross weight and some pavement parameters. It increases exponentially with the axle loads., it is important to know the weight of each axle. The analysis of the traffic was made taking into account the measurements made over the last 5 consecutive years from 2009 to 2013 in order to identify any evolutions attributable to the measure studied. The graph below presents for each year the variation between the value measured by the equipment WIM and the trend observed over the 2009 - 2012 period.

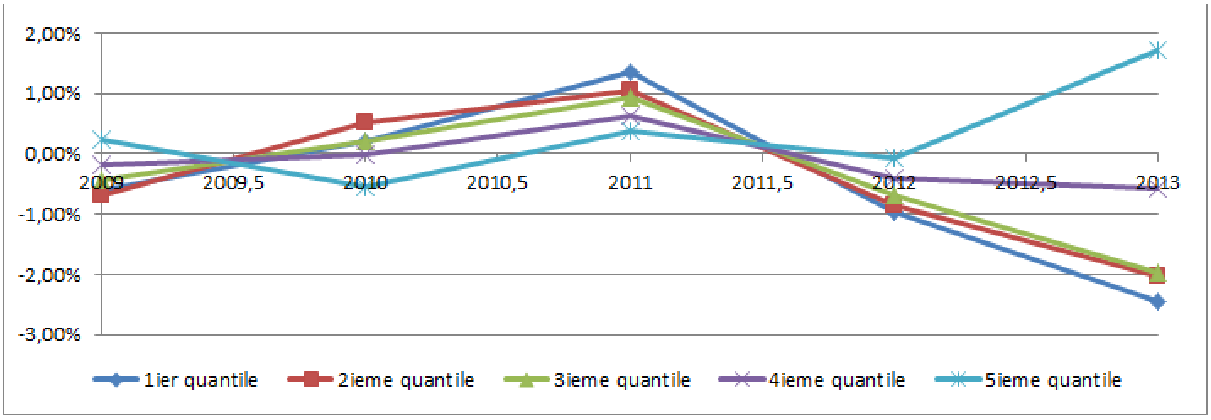

Figure 5 – Variation of the weights of each quintile in relation to the trend.

There is a drop in the tonnage transported by the first quintiles since 2011; from the 4th quintile this decrease is less important. For the last quintile, which includes the most loaded vehicles (above 38.6 tons in 2013), the average weight increases significantly in 2013 compared to the trend of previous years.

The main effect of increasing the maximum allowed tonnage to 44 tons has been to reduce the flow of heavy goods vehicles by better filling them. The corresponding decrease in traffic can be estimated at about 0.37%, reduced to about 77 million heavyweights.km.

3.2 Traffic of light commercial vehicles

The study on the counting of light commercial vehicles on the WIM equipment network aims to evaluate the evolution of the traffic of foreign light commercial vehicles on French territory. It responds to a request from the DGITM, following various requests from professional organizations and reports from the DREAL transportation controllers, which seemed to indicate a uniform increase in France of international competition in the light freight transport sector.

Types of vehicles likely to be involved in light freight traffic correspond to the following vehicles: vehicles with tarpaulin chassis; with chassis-cab with body; with advanced cab and van type vehicles, they do not have a "characteristic profile" that is easily identifiable automatically by a measurement system and these vehicles can be discriminated and sorted by nationality only visually from their silhouette and registration. The WIM equipment is the most "adapted" system that allows the visualization of vehicle data, remotely, without operator in the field. This equipment provides the individual data of all vehicles traveling on the instrumented sensor tracks. For each van exceeding a threshold (speed and weight), profile and license plate photographs are stored with other measurements on a remotely accessible server.

A visual analysis was then carried out in order to keep only the types of vehicles likely to be involved in the light fret transport and to discriminate in these vehicles french and foreigners, according to the rule of classification by nationality of registration.

According to the average annual daily traffic data of 10 WIM equipment in 2017, light commercial vehicles represent 9% of the whole traffic while heavy traffic represent 17% of the whole traffic.

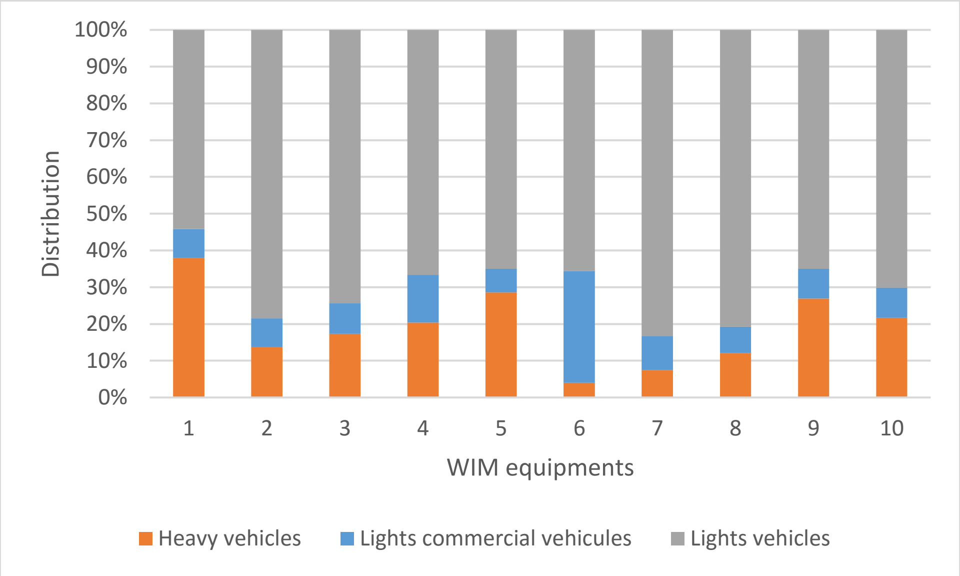

Figure 6 – Distribution of heavy and light commercial vehicles according to the average annual daily traffic of 10 WIM equipment in 2017

The other results of this study can not yet be published.

3.3 Knowledge of heavy traffic for the company Eurotunnel

This study (Stanczyk, Klein, Purson and Absalon, 2013) answered two concerns of the Eurotunnel group expressed as part of the restructuring of the Calais freight terminal:

- Better understand the characteristic lengths of heavy vehicles;
- Look for parameters to identify "just" empty vehicles.

The length distributions for the 15 most representative heavy vehicle categories were provided in the final report of the study. They have allowed Eurotunnel to better know the average lengths of all these vehicles and also the associated dispersions. Some categories of heavy vehicles show a disparity of models which generates distributions of very dispersed lengths.

This study also provided for more than 80% of heavy vehicles a proposal for a combination of parameters to identify empty vehicles from individual measurements of axle loads, groups of axles and total weights.

All results from this study were provided from a finite sample of vehicles and for a full year (2012). At the end of the instrumentation of the terminal and associated measurement points, on-site measurement campaigns were conducted to refine their values.

4 Conclusions

Weigh in Motion systems deployed in France since 2006 carry out an automated screening of overloaded road transport vehicles and provide app. 1 million of trucks recorded every year on each WIM site, which in total represents 30 millions of weightings. Such a rich database is used for targeted local or national studies, mainly for public purposes, but sometime in some public-private partnerships. The use of the equipment WIM database brings a real knowledge of the traffic on these measurement points. The extractions of some data make it possible to provide conclusions on the application of a decree or to provide arguments to put in place some security or control measures.

5 Acknowledgements

Authors express their thanks to the DGITM (General Directorate for Infrastructure, Transports and Sea) of the French Ministry of Ecological and Solidarity Transition, for supporting WIM equipments and allowing Cerema to use the richness of this database.

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PORTABLE WIM AS A TOOL FOR REALISTIC TRAFFIC LOADING FACTORS ON MACEDONIAN NATIONAL ROAD NETWORK

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Abstract
The primary objective of the project was to determine traffic loading (ESAL) information on most trafficked road sections in Macedonia for planning and programming of maintenance treatments in RAMS and to define overall average equivalency factor per vehicle type. The scope of the project assignment was the performance of 20 fortnight Bridge WIM measurements in free traffic flow on most trafficked road sections, analysis of individual and summarized data and preparation of conclusions and proposals for the manager of the national road network in Macedonia, focusing on proposed equivalency factors for individual vehicle types for future distribution on whole road network. Paper will show high usability of WIM data in relation to major planning decision for future steps in road network maintenance and design with focus on realistic traffic loading factors.

Keywords: weigh-in-motion, equivalency factors, road network, overloading.

Resumo
O principal objetivo do projeto foi determinar informações da carga do tráfego (ESAL) nos trechos de rodovias com maior volume de tráfego na Macedônia para o planejamento e a programação de manutenções em RAMS e para definir a média geral do fator de equivalência por tipo de veículo. O escopo do projeto foi a execução de 20 medições quinzenais com Bridge-WIM do fluxo normal de tráfego nos trechos de rodovias mais movimentados, a análise dos dados individuais e resumidos e a preparação das conclusões e propostas para o gestor da malha rodoviária nacional da Macedônia, com foco nos fatores de equivalência propostos por tipos individuais de veículos para futura distribuição em toda a malha rodoviária. O artigo mostrará a alta utilidade dos dados de pesagem em movimento para decisões importantes de planejamento de futuros passos na concepção de projetos e na manutenção da malha rodoviária com foco em fatores realísticos da carga do tráfego.

Palavras-chave: pesar em movimento, fatores de equivalência, rede rodoviária, sobrecarga**.**

1. Foreword

The Public Enterprise for State Roads (PESR) as a manager of the national road network in Macedonia wishes to determine traffic loading (ESAL) information on most trafficked road sections for planning and programming of maintenance treatments in Road Asset Management System (RAMS). According to the project guidelines, Company Cestel performed 20 fortnight Bridge Weigh-in-Motion (WIM) measurements with the SiWIM® systems.

Locations of the measurements were strategically selected to cover as much of road network as possible, not only in road sections length, but also expected traffic loading with data derived from traffic counters. Bridge WIM systems were installed over all of the traffic lanes, that means in both directions on regional roads and on driving, overtaking and slow lane (if exists) on motorway sections. The installation of the equipment was done without making any damage to the road surface and without stopping the traffic.

The calibration of the Bridge WIM systems on every site was done with the r1 conditions (fully repeatability conditions), which means with one typical example of a heavy loads vehicle per site, with 15 runs over each traffic lane.

2. ESAL calculation

Road pavements are structures with finite lives and are designed to withstand a specific number of Equivalent Single Axle Loads (ESALs). The common procedure to evaluate cumulative ESAL value for certain traffic can be described by the formula 1, which is based on AASHO road test (AASHO, 1993) and same theoretical principles, but is more advanced in a sense that it incorporates effects of different types of tires and suspension.

$$FE_{veh} = 10^{-8} \times \sum_{i=1}^{n} f_{a,i} \times (f_{t,i} \times P_i)^4 \qquad (1)$$

where

FE_{veh}	traffic loading of a vehicle, expressed as the sum of individual nominal (equivalent standard) axle loads (ESAL of 80 kN) of the vehicle	
$f_{a,i}$	axle factor, which depends on the type of the axle i:	f_a = 2,4415 for single axle f_a = 0,216 for double axle f_a = 0,0533 for triple axle
$f_{t,i}$	factor of the type of the tire on axle i:	f_t = 1,0 for double tire f_t = 1,2 for super single tire f_t = 1,3 for single tire
P_i	axle loading of axle i (kN)	
N	number of the axles of the vehicle	

Reference axle load (an axle load equal to the reference axle load yields an ESAL value of 1) was related to 80kN and was as such selected by the PESR.

Daily traffic loading on a road section is then calculated as the sum of Equivalency Factors (FE_{veh}) of all vehicles that cross the section in a day.
In this paper the traffic loading on a section is represented with the number of passes of ESAL of 80 kN in a day and marked with $ESAL_{SiWIM}$.

3. Measurement results

The measurements took place from the beginning of September 2017 until the end of November 2017 on locations throughout Macedonian road network on predefined locations (Table 1).

Table 1 – List of road sections with SiWIM® measurements

Road	*Road section (name of the site)*	*Road*	*Road section (name of the site)*
A1	Skopje – Kumanovo (Kumanovo 1)	A2	Gostivar – Kičevo (Kičevo)
A1	Kumanovo – Skopje (Kumanovo 2)	A2	Ohrid – Struga (Struga)
A1	Petrovec – Klučka Hipodrom (Petrovec 1)	A2	Stracin – Kriva Palanka (Kojnare)
A1	Klučka Hipodrom – Petrovec (Petrovec 2)	A3	Bitola – Prilep (Vašarejca)
A1	Petrovec – Negotino (Negotino 1)	A3	Veles – Štip (Peširovo)
A1	Negotino – Petrovec (Negotino 2)	A3	Kočani – Delčevo (Makedonska Kamenica)
A2	Tetovo – Aračinovo (Stopanski dvor 1)	A4	Skopje – Kačanik (Orman)
A2	Aračinovo – Tetovo (Stopanski dvor 2)	A4	Štip – Strumica (Čifilik)
A2	Tetovo – Gostivar (Žerovjane 1)	A4	Strumica – Novo Selo (Sušica)
A2	Gostivar – Tetovo (Žerovjane 2)	R1201	Struga – Debar (Vraništa)

3.1 Accuracy of the measurements

All measurements were required to meet the accuracy class of at least C (Žnidarič et al., 2017), as defined in COST323 European WIM specifications and results are presented in Table 2.

Table 2 – Accuracy classes according to the COST323 specification

	ACCURACY			
Measurement	*Single axles*	*Group of axles*	*GVW*	***OVERALL***
Čiflik	C(15)	C(15)	C(15)	**C(15)**
Kičevo	B(10)	B(10)	B+(7)	**B(10)**
Kojnare	B(10)	C(15)	C(15)	**C(15)**
Kumanovo1	B(10)	A(5)	B+(7)	**B(10)**
Kumanovo2	C(15)	C(15)	C(15)	**C(15)**
Makedonska Kamenica	B(10)	B+(7)	B(10)	**B(10)**
Negotino1	C(15)	B(10)	B+(7)	**C(15)**
Negotino2	A(5)	B(10)	B(10)	**B(10)**
Orman	C(15)	C(15)	C(15)	**C(15)**
Peširovo	C(15)	C(15)	B(10)	**C(15)**
Petrovec1	C(15)	C(15)	C(15)	**C(15)**
Petrovec2	C(15)	B+(7)	B(10)	**C(15)**
Stopanski dvor1	C(15)	C(15)	B(10)	**C(15)**
Stopanski dvor2	C(15)	C(15)	B+(7)	**C(15)**
Struga	C(15)	C(15)	C(15)	**C(15)**
Sušica	C(15)	B+(7)	B+(7)	**C(15)**
Vašarejca	C(15)	C(15)	C(15)	**C(15)**
Vraništa	C(15)	C(15)	C(15)	**C(15)**
Žerovjane1	C(15)	C(15)	C(15)	**C(15)**
Žerovjane2	C(15)	C(15)	C(15)	**C(15)**

Trucks of known weight were used to calibrate all bridge-WIM systems. The appropriate test plan according to the European WIM specifications was selected mainly based on the target accuracy and confidence in the results. For simpler calibrations, measurements in repeatability conditions (with 1 calibration vehicle only), are sufficient.

European WIM specifications define a test plan, achieving 95% confidence levels π_0 of the results with one fully loaded truck and at least 10 runs per lane in total. 15 runs were performed per lane, 9 runs with average speed of the traffic, which was also maximum allowable speed on that road section and 6 runs with 80% of the maximum allowable speed.

A shorter 2 or 3-axle rigid truck is recommended for calibration as it better indicates possible dynamic problems and necessity for velocity calibration. They are more sensitive to uneven pavement and bumps before the bridge as the longer non-rigid vehicles, thus providing a conservative upper-bound indication of the accuracy of WIM results.

Accuracy of SiWIM results depends on type of the structure, quality of installation, type of calibration and particularly on evenness of the pavement on the approach to the bridge. It is recommended to evaluate accuracy of SiWIM results according to the European Weigh-in-motion specifications (COST 323, 1999). SiWIM® results should be compared to the weighing results of the same vehicles obtained on a scale that is at least 3 classes more accurate than the WIM system. For Macedonian WIM measurements requirement was to achieve accuracy class better or equal than C(15). The only alternative for the reference weighing is to use static scales.

COST 323 specifications define an accuracy class with a letter and a number in the parentheses. Class A(5) is the most accurate one and is followed by classes B+(7), B(10), C(15), D+(20), D(25) and E(30). The number in parentheses is the confidence interval δ at the confidence level π of approximately 95 % of all results. The exact level of confidence depends on the number of test vehicles, on the type of the check (initial calibration or subsequent validation) and on test and environmental conditions.

The confidence intervals vary depending on the accuracy class and the criteria (gross vehicle weight, single axles, group axles and axles from a group). Tables of accuracy according to European WIM specifications provide results for each individual criterion (gross weight, single axles, axle groups and axles from a group) in terms of two levels of confidence: π_0, which is the confidence level for the achieved confidence interval δ and π, which is the confidence level for the attained accuracy class and is generally higher than π_0.

Unevenness (bump or settlement) before the bridge can result in non-linear relationship between the velocity and the evaluated weights. Consequently, vehicles are pushed up depending on their suspension and speed which affects their actions on the bridge. This causes redistribution of axle loads (depending on the velocity, the first axle usually gets less loading, the difference is redistributed to the other axles) and error in gross vehicle weight calculation (if bridge is shorter than app. 10 m), vehicles 'fly' over the bridge (Žnidarič et al., 2010).

3.2 Results by vehicle types

Different vehicles were grouped in vehicle types and results of measurements were presented according to this types. Following vehicle types are used:

- vehicle type 5 Truck (> 3,5 tons)
- vehicle type 6 Truck with trailer
- vehicle type 7 Tow
- vehicle type 8 Bus and Bus with trailer.

The results are expressed with the average number of vehicles (classes 5 to 8) per day. According to the number of vehicles, sites are significantly different. Sites on the motorways have on average between 400 and 1.000 heavy vehicles per day, where sites on a regional roads can have as low as 100 heavy vehicles per day, as it can be also seen in Figure 1.

Traffic loading, expressed in ESAL values per vehicle type on each measuring site is shown in Figure 2. Significant differences in ESAL values on different sites are in direct relation with actual location of the measurement and type of traffic on that location. If only transit traffic is expected, then ESAL values for heavy trucks are lower (Petrovec 1 and Petrovec 2), where the location is close to construction sites, quarries, local industry or agricultural activities, values can be quite high, as seen in Sušica or Stopanski dvor 1 and Stopanski dvor 2.

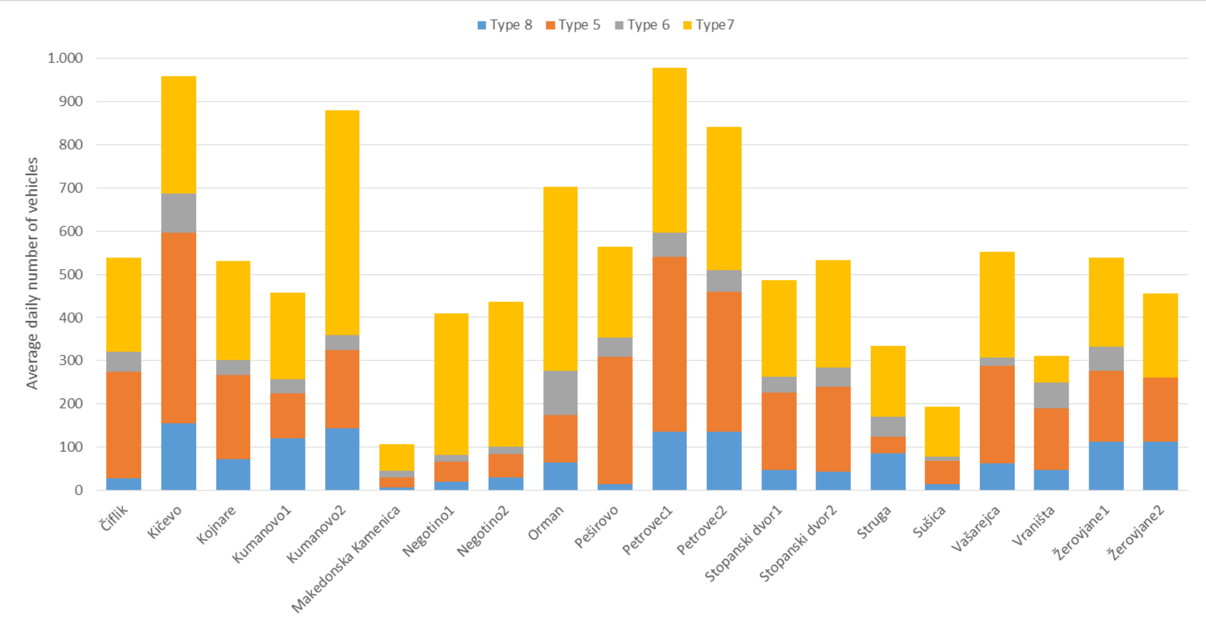

Figure 1 – Average daily number of vehicles per site according to the vehicle type

Overall average FE_{veh} factors per vehicle type were also calculated in Table 3. They represent average ESAL value per vehicle type according to the collected data on 20 sites on a specific dates (Figure 2). Season, road section and site specifics should be considered during evaluation of the calculated average overall values.

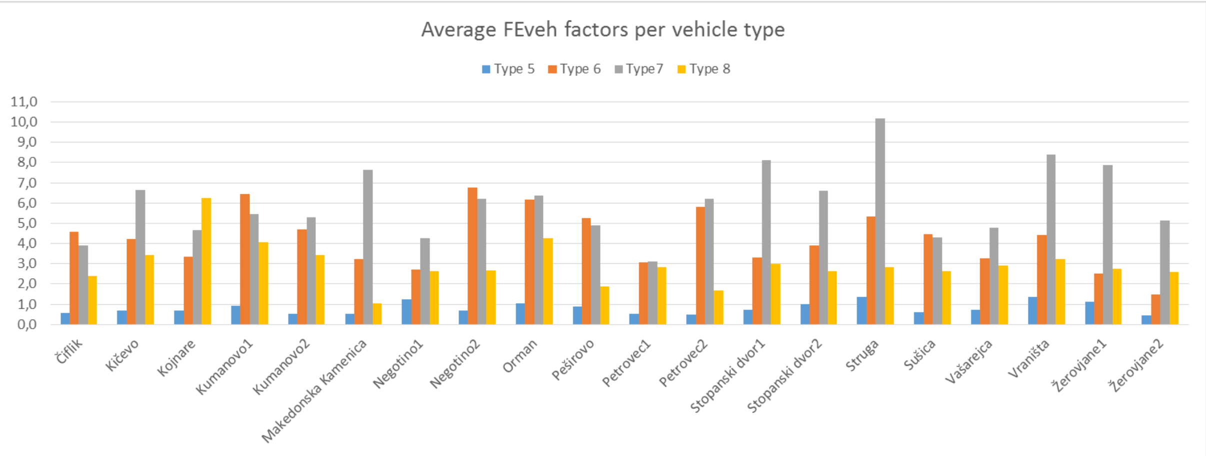

Figure 2 – Average FE_{veh} per site

Table 3 – Calculated average overall Equivalency Factor - FE_{veh}

Vehicle type	*Type 8*	*Type 5*	*Type 6*	*Type7*
Equivalency Factor FE_{veh}	2,95	0,80	4,24	6,00

4. Proposed overall average equivalency factors for individual vehicle groups

As presented in Table 3 average Equivalency Factors for vehicle types were calculated. Analyzing each individual type of the vehicle, specifics were observed and some adjustments are required to calculated values.

Traffic structure differs significantly on different types of roads. All motorways were showing high share of trucks with trailers and taws, where regional roads were more occupied with trucks. Rigid trucks have on average lower FE_{veh}, but their impact on the pavement could not be neglected, as they tend to overload axles higher than other types of vehicles.

In type 8 (busses), majority of individual site equivalency factors were under average overall FE_{veh}, but 8 of them with values above this value. Due to the fact, that values above the average are dominantly from sites with the most of traffic, minor adjustment should be applied to average overall Equivalency Factor. Taking into account amount of vehicles on individual sites, proposed adjusted overall average equivalency factor for vehicles type 8 **FE_8** is **2,7 ESAL 80kN**.

Trucks with total mass over 3,5 tons, vehicles type 5, have quite the opposite situation with majority of motorway traffic being under or around the average value. Since they represent majority of the traffic, and due to the fact, that on regional roads significantly overloaded trucks are expected, proposed adjusted overall average equivalency factor for vehicles type 5 **FE_5** is **0,9 ESAL 80kN**.

Trucks with trailer, vehicles type 6, have FE_{veh} between 2,5 and 6,7, with motorway sites showing typical behavior, where empty vehicles (lower FE) are travelling in one direction and fully loaded (higher FE) in the opposite. Average value is quite good representation of actual situation on Macedonian roads, so proposed adjusted overall average equivalency factor for vehicles type 6 **FE_6** is **4,4 ESAL 80kN**.

Tows, vehicles type 7, have FE_{veh} between 3,1 and 10,2, which is quite a wide range. The highest FE's are measured on sites, where either construction works are in vicinity, or queries, mines or other industry causes vehicles to significantly overload. Analyzing all different types of tows yields results, that are lower than calculated average for 0,6 due to the fact, that transit tows are usually not overloaded and should present significant part of all vehicles. Taking into account all relevant information leads us to proposed adjusted overall average equivalency factor for vehicles type 7 **FE_7** as **5,4 ESAL 80kN**.

All above mentioned equivalency factors are presented also in Table 5.

Table 5 – Final proposed average overall Equivalency Factors

Vehicle type	FE_{type}	**ESAL**
Type 8 (bus)	FE_8	**2,7**
Type 5 (trucks)	FE_5	**0,9**
Type 6 (Trucks with trailers)	FE_6	**4,4**
Type 7 (Tows)	FE_7	**5,4**

5. Conclusions

The measurements took place from the beginning of September 2017 until the end of November 2017 on locations throughout Macedonian road network on predefined locations. Since all measurements were performed in autumn, traffic might be specific for this season; measurements in different seasons are suggested.

Reference ESAL values, used in this report are related to 80kN reference axle. In majority of EU countries, reference axle used is 100kN, so ESAL values, calculated in Macedonia are at least 2,2 higher than values with different reference axle. Average ESAL values for heavy vehicle in countries like Sweden, Finland, Germany or Slovenia are in the range of 1,1 ESAL. Even with all this taking into account, average ESAL value in Macedonia was calculated to 3,81 ESAL, significantly higher than any expected average (Žnidarič et al, 2011).

Generally, overloading in EU ranges between 5% and 20%, depending on type of the road and location of the measurement. Average overloading in Macedonia was slightly above this values. Heavily overloaded vehicles are destroying pavement significantly faster than anticipated from legally loaded vehicles.

Different types of vehicles have different impact on the pavement, but no finite conclusion should be made just according to average ESAL value per vehicle type, because the range of the values for individual vehicles and also for different measurement locations varies significantly. Value for type 5 vehicles (rigid trucks), as an example, can be as low as 0,1 and as high as 7. Types of rigid trucks should be more diverse, divided between light trucks (up to 7,5 tons), medium heavy trucks (7,5 tons to 18 tons) and heavy trucks (3 and 4 axle trucks with GVW up to 32 tons).

Proposed overall average Equivalency Factors are summarized suggestion, calculated from all available measurements on different measurement sites. They differ significantly not only from site to site but also form lane to lane. It is important to understand, that due to the asymmetry in loading, to use different factors on different sites and to always use more trafficked lane as reference for any calculation. Proposed overall average Equivalency Factors are suggested according to overall calculation and are not related to the type of the road. We suggest separating this factors to different types of roads (Motorways/regional/local roads).

Traffic on certain road sections is very specific for that area and do not necessary represent general traffic; selection of other road sections for the measurements is proposed.

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Session 2 : B-WIM Technology

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AXLE LOAD CHARACTERISTICS OF THE SWEDISH ROAD NETWORK BASED ON BWIM MEASUREMENTS

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Abstract

One of the key parameters in predicting the deterioration development of pavements is linked to the characteristics of heavy traffic. The heavy traffic loading has been commonly expressed in pavement design methods through an equivalent number of repetitions of standard axle loads (ESAL's). With improved pavement distress models used in recent mechanistic pavement design methods more detailed description of the heavy traffic is needed. In Sweden, a Bridge-Weigh in Motion (BWIM) system has been used to collect information on the heavy traffic carried by the road network. A national BWIM programme was established in Sweden in 2004, consisting of fourteen locations where data is collected annually during one week. The programme contains motorways, arterials or trunk roads as well as one county road. Based on the data, Axle Load Spectra (ALS) has been established from the stations that provides the load distribution of steering axles, other single axles, tandem and tridem axles. The paper presents the ALS and discuss their changes through the eleven year period from 2006 – 2017.

Keywords: Pavement, Heavy Vehicles, Axle Load Spectra, Weigh-in-Motion, WIM.

Résumé

L'un des paramètres clés permettant de prévoir l'évolution de la détérioration des chaussées est lié aux caractéristiques du trafic intense. La forte charge de trafic a été communément exprimée dans les méthodes de conception de la chaussée à travers un nombre équivalent de répétitions de charges à l'essieu standard (ESAL). Avec les modèles améliorés de détresse de la chaussée utilisés dans les méthodes de conception mécanistes récentes, il est nécessaire de fournir une description plus détaillée de la circulation dense. En Suède, un système Bridge-Weigh in Motion (BWIM) a été utilisé pour collecter des informations sur le trafic lourd acheminé par le réseau routier. Un programme national de BWIM a été mis en place en Suède en 2004 et consiste en 14 localités où les données sont collectées chaque année pendant une semaine. Le programme comprend des autoroutes, des artères ou des routes nationales, ainsi qu'une route de comté. Sur la base des données, des spectres de charge par essieu (ALS) ont été établis à partir des stations qui fournissent la répartition de la charge des essieux directeurs, des autres essieux simples, des essieux tandem et tridem. Le document présente la SLA et discute de ses modifications au cours de la période de onze ans allant de 2006 à 2017.

Mots-clés: Structure de la route, dégradation, véhicules lourds, spectres de charge par essieu, pesée en mouvement, WIM.

1. Introduction

Pavements deteriorate due to heavy traffic loading and their exposure to the ambient climate. One of the key parameters in predicting the deterioration process is linked to the characteristics of heavy traffic. The heavy traffic loading is frequently expressed in pavement design methods through an Equivalent number of repetitions of Standard Axle Loads (ESAL's). New pavement performance models used in mechanistic – empirical (M-E) pavement design methods require more diligent information regarding the traffic characteristics than in previous empirical methods where traffic data have usually been aggregated into ESAL's (Lu and Harvey, 2006). Weigh-In-Motion (WIM) systems measure continuously and store axle loads and axle spacing data for each vehicle, as well as date and time, speed and lane direction. Based on this information Axle Load Spectra (ALS) can be constructed. An axle load spectrum presents the load distribution of the vehicle axle groups during a specified period of time. The system provides further the gross vehicle weights and their distribution throughout the day.

In Sweden, a Bridge Weigh-in-Motion (BWIM) system has been used to collect information about the heavy traffic on the road network (Winnerholt and Persson, 2010). A national BWIM programme was established in 2004, consisting of fourteen locations where data is collected during one week annually (The Swedish Road Administration, 2006). The programme contains of motorways, arterials or trunk roads as well as a county road. This, therefore provides a basis to establish an Axle Load Spectra (ALS) which delivers the load distribution of steering axles, other single axles, tandem and tridem axles. As very few quad axles are registered they have been ignored. The load distribution throughout the day is also gathered.

The objective of this paper is to provide information on the current axle loads from the heavy traffic in Sweden and how it has developed during the last eleven years. This is done by expressing the data as ALS. Further, the gross vehicle weight distribution and their hourly distribution throughout the day is discussed.

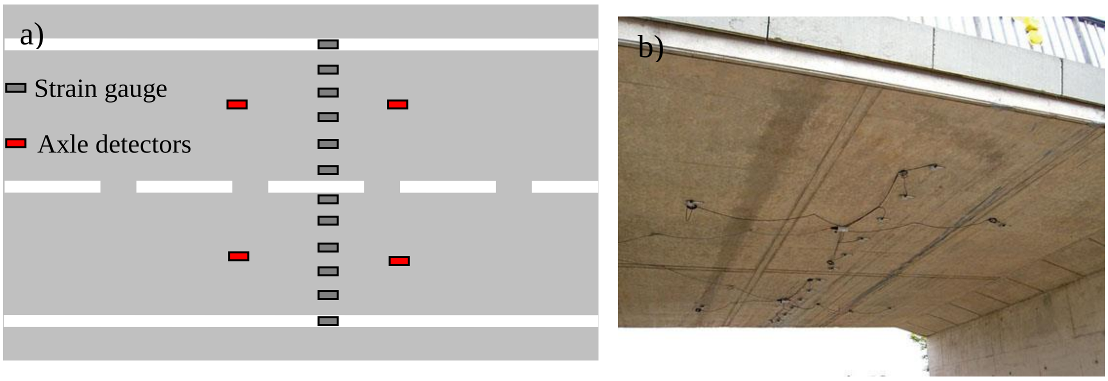


Figure 1 – a) The BWIM consist of two sets of extensometers, one set (four sensors) for detecting the axles and the other set (strain gauges) for weighing the axles, b) extensometers mounted on the bottom of a slab of a concrete bridge

2. The BWIM system

The Swedish BWIM is a portable system mounted on concrete bridges (Znidaric et al., 2005). The system consists of extensometers (strain gauges) and a data logger (Figure 1). Two sets of strain gauges are attached to the bottom surface of the bridge slab. Two pairs of extensometers work as axle detectors. As a vehicle is passing over the bridge they register the time and speed of the vehicle along with the vehicle axle configuration (number of axles, their type as well as the distance between the axles). The strain induced by the different vehicle axles are detected by a row of extensometers and gives their axle loads. All information is thereafter stored in the data logger. Depending on the bridge width, eight or twelve extensometers are used for weighing the axle. The system is calibrated to give correct axle load values. Before and after each measurement period a least ten load passes of a heavy vehicle are used to calibrate the results. Typical results are shown in Table 1. The contribution from light traffic (automobiles) are removed from the data sets. Thus only vehicles with a total weight > 35 kN (3.5 t) are registered. Furthermore, the system is programmed so that two or more suggestive axles are considered to belong to the same axle group if their reciprocal distances are less than 1.8 m.

Table 1 – Typical results from a WIM calibration. Station Skurup in July 2016.

Pass	clc	Ax config	GWV [ton]	W1 [ton]	W2 [ton]	W3 [ton]	W4 [ton]	W5 [ton]	W6 [ton]	W7 [ton]	Ax1 [m]	Ax2 [m]	Ax3 [m]	Ax4 [m]	Ax5 [m]	Ax6 [m]	Tot Ax [m]
1	98	12211	59.82	6.71	9.43	9.43	7.52	7.52	9.61	9.61	4.26	1.36	5.09	1.41	3.91	1.80	17.83
2	98	12211	58.52	6.61	9.43	9.43	7.05	7.05	9.47	9.47	4.23	1.41	4.95	1.41	3.95	1.82	17.77
3	98	1222	57.13	6.35	9.25	9.25	6.91	6.91	9.24	9.24	4.26	1.38	5.06	1.42	3.91	1.78	17.81
4	98	12211	57.75	6.64	9.25	9.25	6.98	6.98	9.32	9.32	4.18	1.44	4.99	1.39	3.91	1.80	17.70
5	98	1222	58.04	7.19	9.24	9.24	6.95	6.95	9.23	9.23	4.27	1.36	5.09	1.41	3.91	1.77	17.81
6	98	1222	58.51	6.70	9.40	9.40	7.01	7.01	9.50	9.50	4.27	1.41	5.00	1.36	3.95	1.77	17.77
7	98	12211	59.52	6.89	9.50	9.50	7.20	7.20	9.62	9.62	4.22	1.41	5.01	1.41	3.86	1.80	17.70
8	98	12211	58.44	6.80	9.31	9.31	7.07	7.07	9.44	9.44	4.27	1.39	4.99	1.39	3.95	1.80	17.79
9	98	1222	58.19	6.66	9.35	9.35	6.94	6.94	9.47	9.47	4.22	1.36	5.01	1.36	3.91	1.76	17.61
10	98	12211	58.05	6.73	9.25	9.25	7.00	7.00	9.40	9.40	4.26	1.35	5.04	1.39	3.86	1.82	17.72
11	98	12211	58.83	6.79	9.40	9.40	7.09	7.09	9.53	9.53	4.27	1.44	4.94	1.39	3.95	1.80	17.79
Mean:			58.44	6.73	9.35	9.35	7.06	7.06	9.44	9.44	4.24	1.39	5.01	1.39	3.92	1.79	17.75
Calibrated truck (ton):			58.28	7.30	9.11	9.11	6.98	6.98	9.39	9.39	4.28	1.38	5.05	1.37	3.99	1.83	17.90
Difference [%]			0.27	-7.78	2.58	2.58	1.18	1.18	0.49	0.49	-0.83	0.78	-0.70	1.79	-1.84	-2.09	-0.82
St. dev. (ton)			0.727	0.196	0.086	0.086	0.162	0.162	0.127	0.127	0.030	0.030	0.048	0.018	0.032	0.019	0.063

Clc = Vehicle class; Wi = weight of axle i; Axi = distance between axle i and i+1, Tot Ax = distance between first and last axle.

In Table 1 eleven passes were conducted with a heavy vehicle of known axle loads and axle spacing’s. The vehicle was a tractor consisting of steering axle and a tandem axle with a trailer with a tandem axle and two single axles (type 12211). The system is set to classify all axles with distances < 1.8 m as belonging to the same axle group. As seen in the table four times the system misses the trailers single axles and classifies them as a tandem axle. This is due to that the distance between the two last axles (axle 6 and 7), which is 1.83 m, but the system registered in four measurements as 1.78, 1.77, 1.77 and 1.76 m respectively. The standard deviation is 0.019 m. Thus 30% of the two single axles passes are therefore expected to classify the two single axles as one tandem axle (here four out of eleven are classified as tandem).

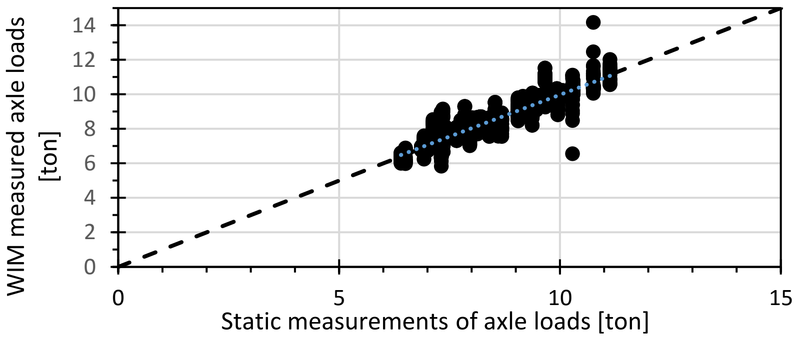


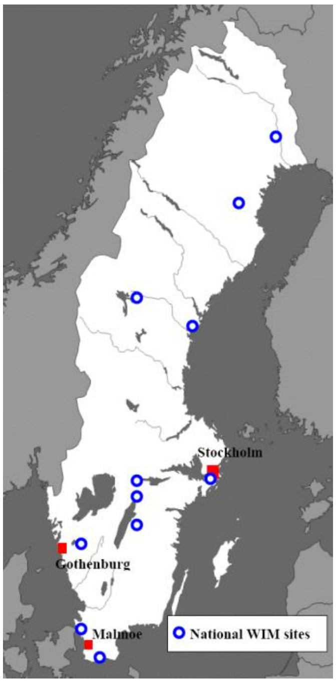
Figure 2 – The dynamic axle weight vs the static axle load for all calibrated vehicles at all stations in 2016. The black dotted line is the 1:1 line.

The difference in the observed mean of the eleven vehicles and their respective calibrated values (for both axle- weight and distances) are relatively low (< ±3%) except for the weight of the steering axle in which the mean underestimates the weight with almost 8%.

The dynamic weight as observed by the BWIM system versus the known static weight for all calibration vehicles at all stations in 2016 are shown in Figure 2. All together this is 1654 axle load measurements. The best fit line through the data set gives $y = 0.97x + 0.29$ with $R^2 = 0.87$.

3. The National Sites

The national sites in Sweden consisted of 14 locations when initiated in 2004. The number has then been increased and in 2017 the number of sites are 16. At each site measurements are carried out during one week every year. The sites geographically cover the whole country, however with more concentration in the southern part as most of the traffic is there. Here, only the initial 14 sites are included, as the objective is to study the changes in ALS over time. Eight of the sites are on motorways; three are arterial or truck roads and one is a county road. Figure 3 shows the geographical location of the measurement stations and provides a short overview of the type of road facility.



Road type	Road no.	Station name	No. of lanes
M	E4	Torsboda	1 + 1
M	E4	Mjölby N	2
M	E4	Mjölby S	2
M	E6	Löddeköping N	2
M	E10	Grundträskån	1 + 1
M	E14	Torvalla	1 + 1
M	E18	Rådmansö	1 + 1
M	E20	Marieberg	2
M	E65	Skurup	1 + 1
A	Rv40	Landvetter W	2
A	Rv40	Landvetter E	2
A	Rv50	Gärdshyttan	1 + 1
A	Rv73	Västerhaninge	2
C	Lv373	Storlängsträsk	1 + 1

Figure 3 – Location of the National BWIM sites in Sweden along with some basic information of the sites.

4. Axle load distribution

The analysis of the BWIM data is straight forward. The data is gathered together into groups, giving the steering, single, tandem and tridem axles. As the number of quad axles is very limited (usually less than 2 per day) they have been omitted. The data is then represented in histograms, here using a bin width of 10 kN (1.0 t). Even though WIM systems give quite detailed information about the traffic characteristics, there are still important parameters concerning the development of pavements deterioration which are not provided, such as the characteristics of the distribution of lateral wander of heavy traffic and tire pressures as well as information regarding single versus twin tire configuration of the individual axles.

Figure 4 and 5 shows the ALS for two sites, the E4 Mjölby N site and E65 Skurup site. The frequency of the ALS is normalized to represent the normalized amount of each axle load type.

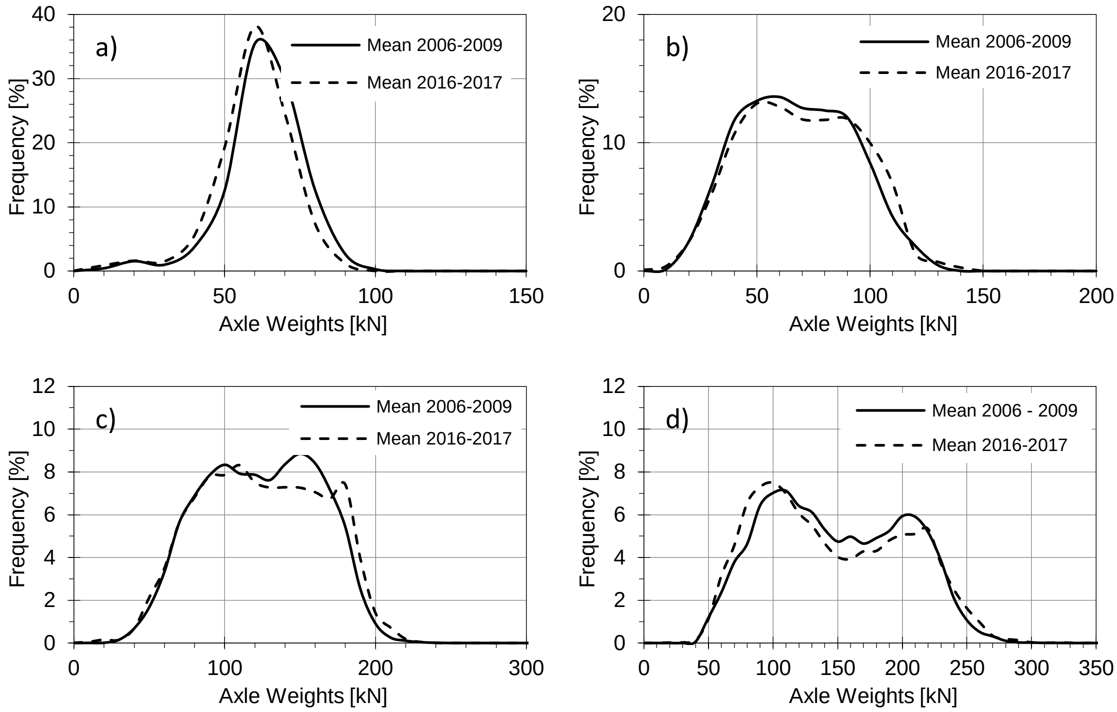


Figure 4 - ALS at the national site E4 Mjölby N. Average values are shown for the years 2006 – 2009 and 2016-2017 respectively. a) Steering axles, b) single axles, c) tandem axles and d) tridem axles.

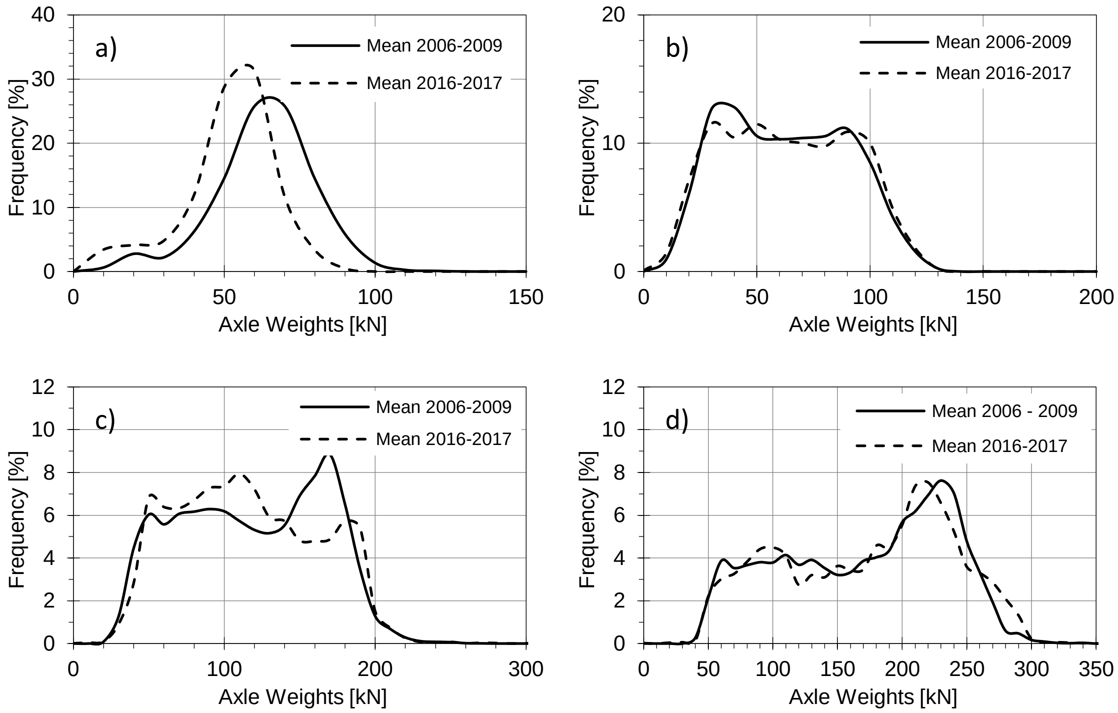


Figure 5 - ALS at the national site E65 Skurup. Average values are shown for the years 2006 – 2009 and 2016-2017 respectively. a) Steering axles, b) single axles, c) tandem axles and d) tridem axles.

One can see in Figure 4 that there are only small changes in the average spectra for the station E4 Mjölby N in 2006 – 2009 and 2016 - 2017 respectively, indicating that the heavy traffic has been very stable during this eleven years period. Larger difference is observed in the spectra for the station E65 Skurup. In Figure 5 in particular it seems that the average steering axles are becoming lighter and very heavy tandem axles are fewer. Further, it can be seen by comparing Figure 4 with Figure 5 that the ALS are different for these two locations. This is also true for other sites, that is the ALS is highly site specific and one general spectra does not covers all the sites.

The BWIM stations give further information about the distribution of the gross vehicle weight, speed and traffic flow during the day. Examples for the same previous stations as before are shown in Figure 6.

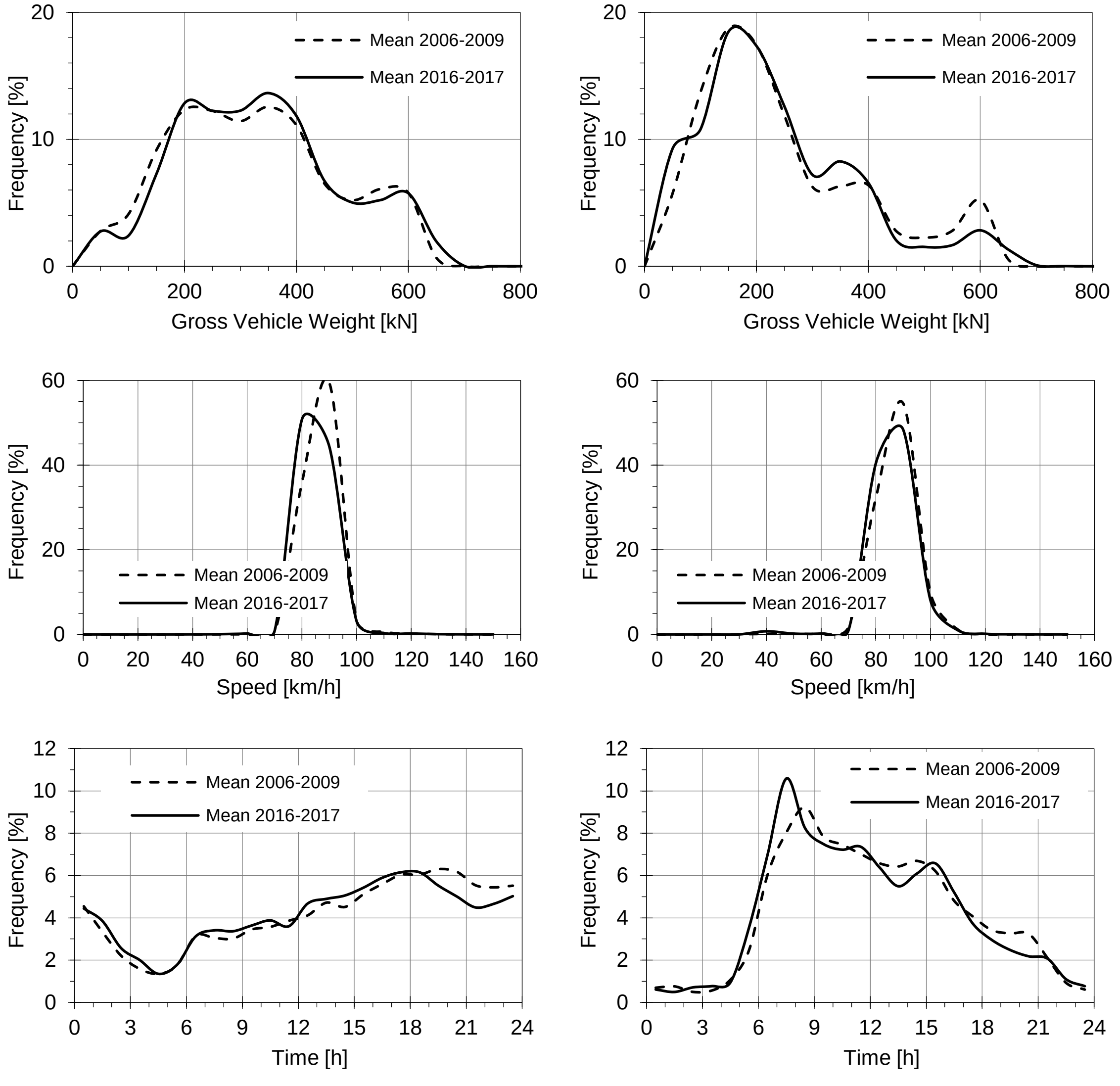


Figure 6 - Gross vehicle weight, speed and traffic flow during the day for two stations. E4 Mjölby N on the left hand side and E65 Skurup on the right hand side.

Figure 6 depicts that the distribution of gross vehicle weight is different at these two stations although the observed maximum vehicle weight is very similar at both sites. Note that the maximum allowed vehicle weight in Sweden has been 640 kN (was increased to 740 kN on 1

July 2018 for part of the road network). Less than 2% of the total vehicles at these sites have weight above this value. The speed limit is 90 km/h at both sites and the majority of the vehicles are keeping that limit. The average speed of the heavy fleet is slightly higher at the E65 Skurup site and in 2009 almost 14% of the vehicles were above the speed limit, in 2017 it has been reduced to about 8%. The distribution of the heavy vehicles throughout the day is very different between the two sites. Most of the national sites show a distribution like the one at the E4 Mjölby N site. i.e. the flow gradually increase from around 5:00 until it reach a maximum around 18:00 were it starts to decrease. The E65 Skurup site rises very quickly from 4:00 and reaches a peak around 08:00 and starts to decrease gradually thereafter until midnight. The E65 Skurup motorway serves the Skurup airport that probably affects the daily distribution of the heavy traffic flow.

One simple way to compare the composition of the ALS between the eleven sites is to calculate their truck factor T_f (average load equivalency factor of each heavy vehicle) using the forth power law, as

$$T_f = \frac{1}{N_{hv}} \cdot \sum_{i=1}^{4} N_i \cdot \sum_{j=1}^{n_j} \left(\frac{W_{ij}}{W_{i_{stand}}} \right)^4 \cdot \frac{f_j^{norm}}{100} \tag{1}$$

where N_{hv} is total number of heavy vehicles during the measuring period, W_{ij} is the axle load of axle i, j where i represents the different axle categories; steering, single, tandem and tridem, j represents the different axle weights, N_i is the number of axles in each category, f_i^{norm} is the normalized frequency (%) of each axle weight and $W_{i_{stand}}$ is the weight of the respective standard axle category, thus steering (100 kN), single (100 kN), tandem (180 kN) and tridem (240 kN) respectively. The truck factor of all the sites for all analysed years is given in Figure 7.

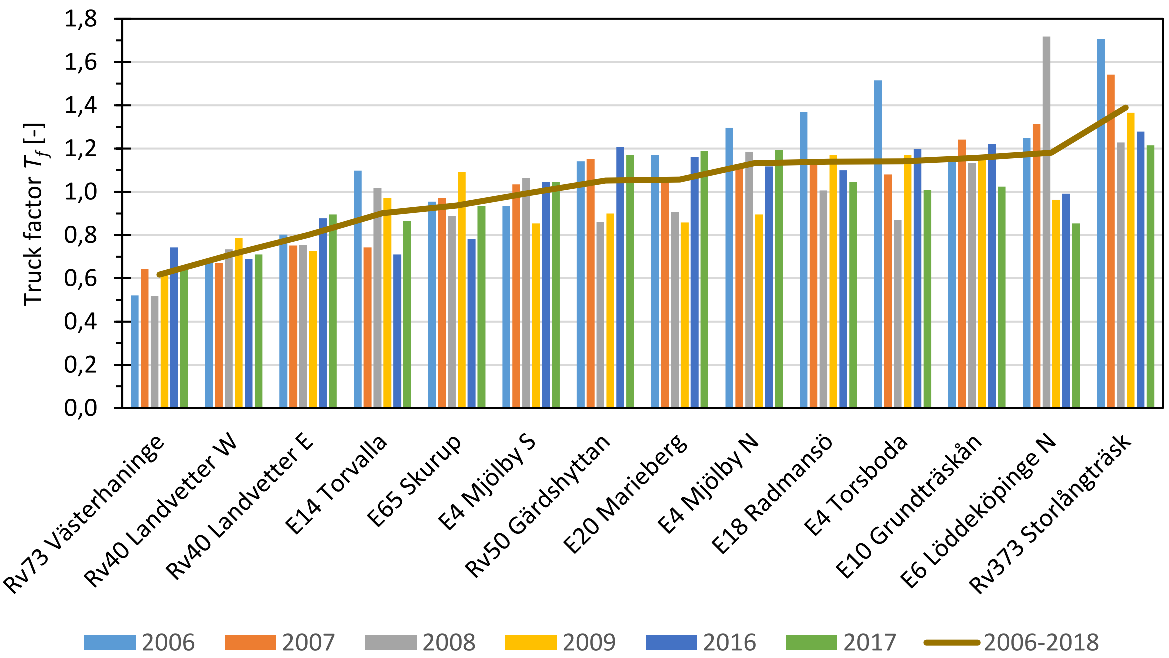


Figure 7 - The truck factor T_f for all stations and all analysed years plotted from the smallest to the largest.

Figure 7 shows that the truck factor varies in average from 0.62 to almost 1.39. Most stations show some variations between individual years.

5. Discussion

A new mechanistic-empirical (M-E) approach for pavement design is under development in Sweden. The aim is to predict the structural degradation of road structures as a function of time (Erlingsson and Ahmed, 2017). The calculation scheme is based on two main steps; a response calculation step for the different traffic loads applied, taking into account the ambient climate, and a performance prediction step where pavement degradation is predicted in time steps and subsequently accumulated over the entire design period of the pavement structure. A simplified overview of the approach is given in Figure 8.

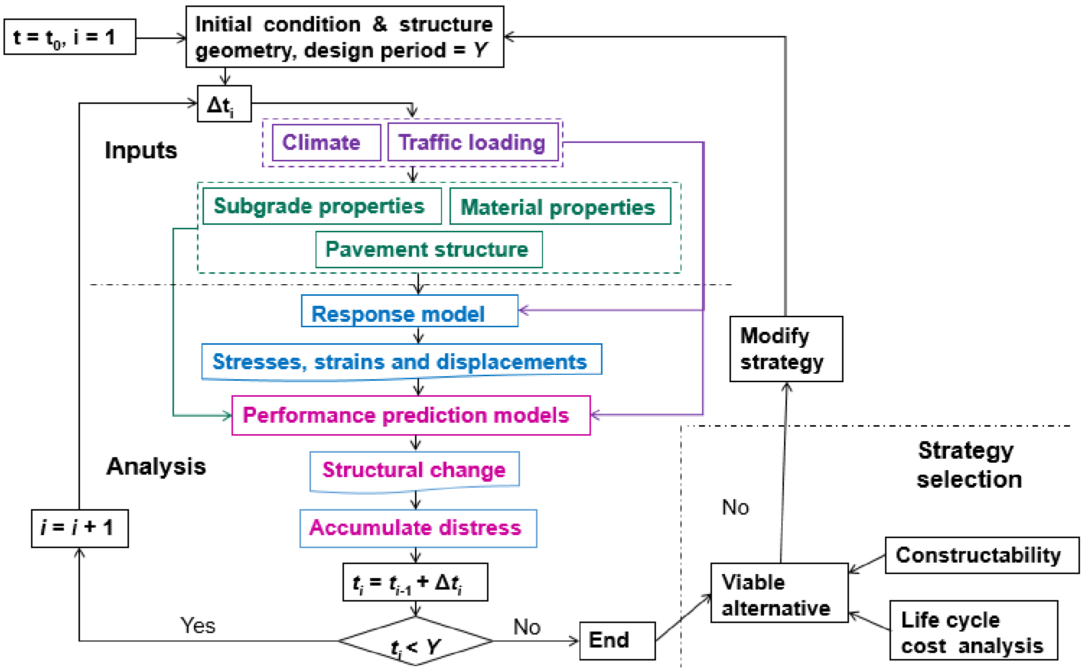


Figure 8 - Overview of the new M-E design and performance prediction approach which is under development.

In the response calculation step of the new M-E design procedure the ALS will be used instead of the number of ESAL´s that is currently being used. With this a more realistic description of the loading will be achieved and should result in more accurate deterioration prediction.

The traffic loading is divided into the four categories; steering, single, tandem and tridem but quad axles are ignored. The bin width is 10 kN. The BWIM system does not provide the information about tire pressures or whether an individual axle consists of single or dual tire configuration. The tire pressure is set as constant with a default vale of 800 kPa (can be changed) and the steering axles are treated as single tire axles but all single, tandem and tridem axles are assumed to have a dual tire configuration. The main reason for this is the lack of accurate information about the share of single versus twin tyre configuration.

An example of the ALS input to the new M-E design approach is given in Figure 9.

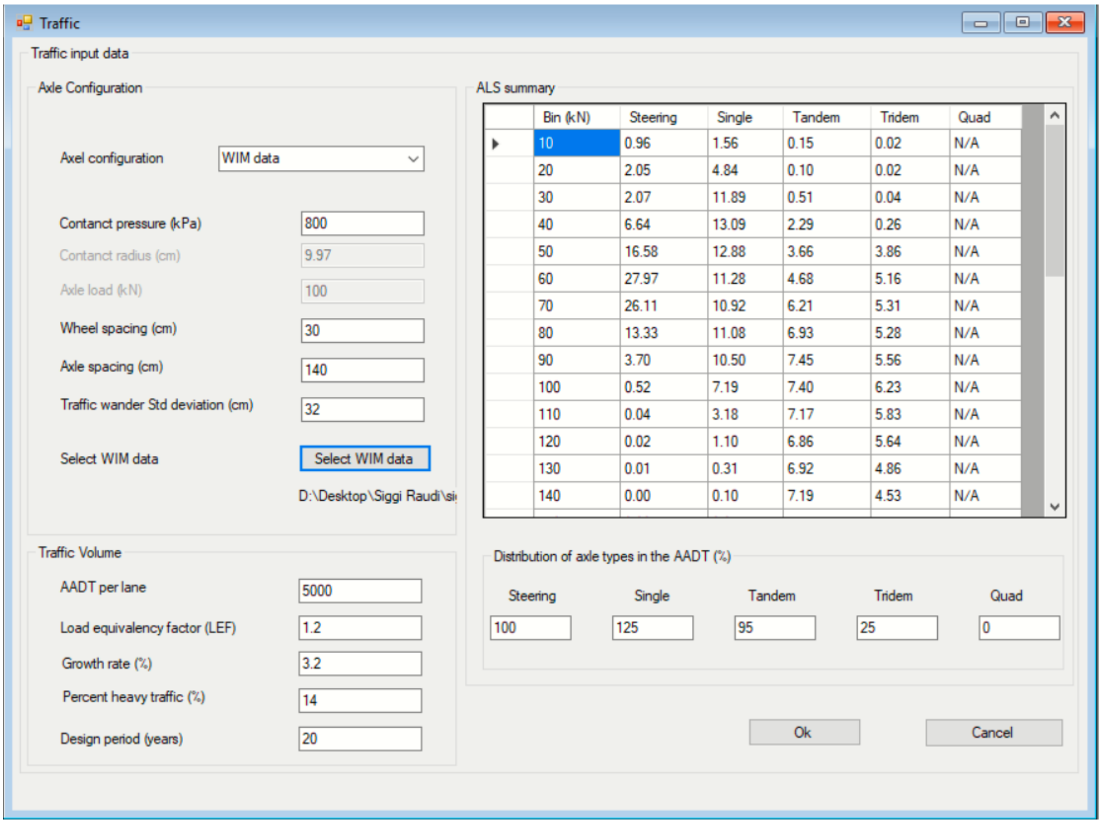


Figure 9 – Example of the ALS input to the new M-E design and performance prediction approach.

6. Conclusions

Heavy traffic characteristics, based on BWIM data, obtained in the years 2006 – 2009 and again 2016 – 2017 from 14 road sites in Sweden have been analysed and presented as ALS distributions. Some of the main findings can be summarized as follows:

- Considerable variations occur between the ALS from different sites. No general ALS can therefore be given that is valid for all the national sites on the Swedish network.
- The development of the weight distribution of heavy vehicles varies between these two time periods. At some stations the distribution has been very stable whereof at others some changes have occurred. How the spectra changes with time is of importance if they are to replace the currently used ESAL´s as an input in the design process of pavement structures.
- The truck factor based on the ALS indicate that the load of axles at the different sites is very site depended.
- Sampling data for one week is sufficient to build reliable axle load spectra for the locations with heavy traffic. This is true for the steering, single and tandem axles. As tridem axles are approximately only 25% as frequent as the other axle types, longer sampling periods would probably improve the accuracy of the spectra. For some of the arterials or truck roads and the county road a longer sampling period is needed to improve the quality of the ALS for all axle types.

As has been previously stated the axle load spectra reviled here are based on a one week sampling period at each site per year. A longer sampling period would probably improve the data leading to more accurate results. However, as measurements are made yearly it should be possible in the future to build up ALS at each site based on accumulated data from a number of consecutive years. This might improve the prediction of the average ALS for the network but changes in the fleet's traffic characteristics between years might on the other hand affect such results.

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THE VIRTUAL AXLE CONCEPT FOR BRIDGE WEIGH-IN-MOTION SYSTEMS

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Abstract

This paper suggests that B-WIM systems can also be used for Structural Health Monitoring simply by performing additional calculations on the measurements. It is theoretically shown that for a given vehicle it is convenient to assume the presence of an additional weightless axle, which has been termed ‘Virtual Axle’ (VA), to detect damage. A change in structural behaviour will lead to weight estimates different to zero for this fictitious VA load by the B-WIM system. The proposed idea can be used to define a new robust output-only model-free level 1 SHM technique. The concept of Virtual Axle is validated here numerically using the results from a vehicle-bridge interaction model. First, one particular example is examined to define an appropriate damage index. Then, a parametric study is performed together with a Monte Carlo simulation to investigate the influence of bridge damage magnitude and damage location.

Keywords: Virtual Axle, Bridge Weigh-in-Motion, Structural Health Monitoring, Vehicle-Bridge interaction

Resumen
Este artículo propone que se pueden usar los sistemas de B-WIM para monitorizar el estado de la estructura simplemente haciendo cálculos adicionales sobre las mediciones realizadas por el sistema. Se demuestra teóricamente que se puede detectar daño estructural si se añade al algoritmo de cálculo un eje de peso cero, que se ha denominado eje virtual (VA). La idea propuesta aquí es un método robusto de SHM de nivel I que no requiere modelo. El concepto de eje virtual es validado de forma numérica con un modelo de interacción vehículo-puente. Primero, se estudia un ejemplo particular para definir un índice de daño (DI). Finalmente, se hace un estudio paramétrico para evaluar la influencia de la magnitud in posición del daño estructural.

Palabras clave: Eje virtual, Bridge Weigh-in-Motion, Structural Health Monitoring, interacción vehículo-puente

1. Introduction

Bridge Weigh-in-Motion (B-WIM) is a well-established technology that has been developed since its introduction by Moses (1979). Over these past decades, multiple improvements have been achieved in all aspects of this technology, which include development of improved algorithms, adequate signal processing and alternative sensor technology. Now that B-WIM has matured sufficiently, there is a trend to find additional uses, not only for the traffic data obtained, but also for existing instrumentation on the bridge. Yu et al. (2016), in a review of recent research on B-WIM systems and applications, highlight that the information extracted from such systems can also be used for the purpose of SHM or vice versa, concluding that the integration would further extend the capabilities and reduce the cost of SHM systems.

Towards that direction, Znidaric et al. (2016) suggest that a combination of B-WIM and SHM system would be a very useful tool for bridge owners. The European project BridgeMon attempted this integration on a railway bridge, as reported in Favai et al. (2014), exploring the use virtual monitoring of bridges. Cantero and Gonzalez (2015) propose that bridge damage can be detected by studying the ratio between weight estimates from two independent WIM systems, one pavement-based and one bridge-based. In Gonzalez and Karoumi (2015), the measurements from a B-WIM installation are used to train a neural network based model that is able to predict bridge responses. The appearance of large discrepancies between measurements and predictions would indicate that damage has occurred.

This paper presents and further elaborates on an additional possibility for SHM using B-WIM systems. The novel idea, which was first introduced in Cantero et al. (2015) shows that it might be possible to infer information regarding the state of a bridge by simply performing additional calculations on the measurements from a B-WIM system. It was theoretically shown, that the introduction of an additional fictitious axle in the B-WIM calculations provides information about changes in the structural response. This extra axle is termed Virtual Axle (VA) and can be used to define an output-only model-free level 1 SHM technique.

This document has been divided into three distinct parts. First, Section 2 gives a summarized qualitative derivation and description of the VA concept. Section 3 tests the novel idea numerically, using a vehicle-bridge interaction model, and explores its application for bridge damage detection. The paper ends with a parametric study that combines the results from a Monte Carlo simulation to examine the sensitivity of the proposed method to bridge damage magnitude and damage location.

2. Virtual Axel Concept

This section introduces the concept of Virtual Axle and provides only a qualitative description of its background. For the complete theoretical derivation, the reader is referred to Cantero et al. (2015).

The main goal of the B-WIM algorithm is to estimate each individual axle weight $\{P_i\}$ for a vehicle with N axles. During installation, the system has been calibrated; obtaining the corresponding influence line $\{I_t\}$ for every sensor location. Then, for each vehicle-crossing event, the system measures the strain $\{\varepsilon_t^{me}\}$ and requires the knowledge of the vehicle's speed, number of axles and distance between them. The axle weights can be found using Moses (1979) algorithm, which minimises the difference between measured strain and theoretical strain $\{\varepsilon_t^{th}\}$. The latter can be calculated with the knowledge of the influence line and the vehicle's axle spacing. The minimization is a least squares analysis that can be expressed in matrix form reducing the problem to a system of linear equations (OBrien et al., 2009) that can readily be solved obtaining estimates of each axle weight.

Over time, the structural behaviour of the bridge might change because of damage or environmental conditions. This means that the response due to a moving unit load is now different. In other words, the current influence $\{\tilde{I}_t\}$ line at a sensor of the B-WIM system has changed with respect to the influence line obtained during calibration. For any subsequent event, the axle weight estimates provided by the system have an inherent error since the influence line has not been recalibrated. This is, the predicted axle weights are computed using the original influence line $\{I_t\}$ whereas the actual measured strain is related to the new influence line $\{\tilde{I}_t\}$. Therefore, the estimated axle weights $\{P_i\}$ are different from the actual axle weights of the traversing vehicle $\{\tilde{P}_i\}$. In the remaining of the document the influence line obtained during calibration is termed healthy influence line, whereas the modified one is termed damaged influence line.

To explore the consequences of using an imprecise influence line, the minimisation problem can be expressed analytically in terms of the variables described above. For the sake of simplicity, the Moses algorithm is derived for the particular case of a vehicle with only two axles. The linear system can be solved, resulting in expressions for the estimated axle weights as seen in Equation (1).

$$\begin{Bmatrix} P_1 \\ P_2 \end{Bmatrix} = \begin{bmatrix} \dfrac{\left(\tilde{P}_1 D_{1,1} + \tilde{P}_2 D_{1,2}\right) H_{2,2} - \left(\tilde{P}_1 D_{2,1} + \tilde{P}_2 D_{2,2}\right) H_{2,1}}{H_{1,1} H_{2,2} - H_{1,2}^2} \\ \dfrac{\left(\tilde{P}_1 D_{2,1} + \tilde{P}_2 D_{2,2}\right) H_{1,1} - \left(\tilde{P}_1 D_{1,1} + \tilde{P}_2 D_{1,2}\right) H_{1,2}}{H_{1,1} H_{2,2} - H_{1,2}^2} \end{bmatrix} \qquad \text{Eq. (1)}$$

where matrix [H] derives from the matrix product of healthy influence lines, and matrix [D] is the result of the matrix product of healthy and damaged influence lines. It is acknowledged that this text does not provide a full description of the terms in Equation (1). (See Cantero et al., 2015)

Equation (1) shows how changes in influence line affect the axle weight predictions for a 2-axle vehicle configuration. It is possible to use this expression to quantify the error due damages on the bridge. However, it is even more interesting to explore further this expression. For instance, if we assume that one of the traversing axles is weightless ($\tilde{P}_2 = 0$) it reduces to Equation (2).

$$\begin{Bmatrix} P_1 \\ P_2 \end{Bmatrix} = \begin{bmatrix} \dfrac{\tilde{P}_1 D_{1,1} H_{2,2} - \tilde{P}_1 D_{2,1} H_{2,1}}{H_{1,1} H_{2,2} - H_{1,2}^2} \\ \dfrac{\tilde{P}_1 D_{2,1} H_{1,1} - \tilde{P}_1 D_{1,1} H_{1,2}}{H_{1,1} H_{2,2} - H_{1,2}^2} \end{bmatrix} \qquad \text{Eq. (2)}$$

Equation (2) shows that the installed B-WIM system provides an estimate for both axles, even though one of the axles traversing the system is known to have no weight. This weightless axle has been termed Virtual Axle (VA) and its properties are listed below:

- The VA is zero if there is no damage, i.e. when $\{\tilde{I}_t\} = \{I_t\}$.
- The VA is zero if the axle distance d is greater than the length of the influence line L (see Figure 1). This result sets the limits of possible axle distances to consider in any VA calculation to the interval $[-L, +L]$.
- The VA is zero if the damaged influence line is a linear transformation of the healthy one, i.e. when $\{\tilde{I}_t\} = \lambda\{I_t\}$ for λ a constant.
- A value of VA different to zero indicates that the influence line obtained during calibration is different in shape to the current influence line of the structure.

Figure 1 shows a schematic representation of the concept of Virtual Axle. An existing B-WIM system would render an actual weight estimate for a fictitious weightless axle if the current influence line has changed in shape with respect to the one obtained during calibration. The derivation of VA was presented for the case of a hypothetical 2-axle vehicle (one real and one virtual). However, it is possible to extend the expressions to vehicles with more axles obtaining the same properties listed above.

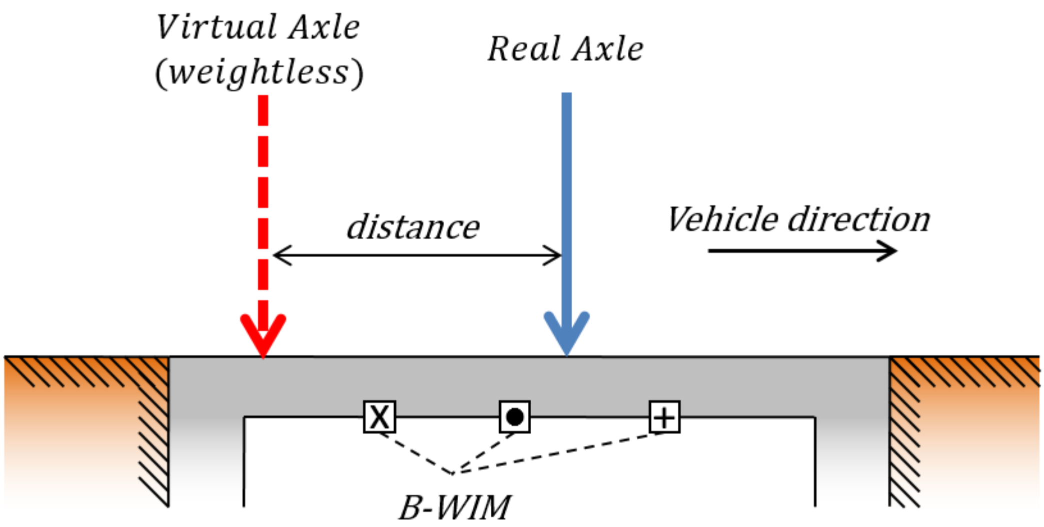

Figure 1 – Schematic Description of Virtual Axle Concept

3. Numerical Validation

The VA concept for an existing B-WIM system is explored numerically using a vehicle-bridge interaction model. Section 2 derived the VA concept for the ideal case of a 1+1 axle vehicle (1 real + 1 virtual axle) considering the ideal static response of the bridge. However, real measurements correspond to the passage of multi-axle vehicles, where the signals are noisy and would include the dynamic response of the bridge. Therefore, this numerical validation uses a vehicle-bridge interaction model that provides accurate dynamic bridge responses for the passage of a 2+1 axle vehicle (2 real + 1 virtual axle). Furthermore, the calculated bridge responses are corrupted with random noise in order to replicate as much as possible a real-case scenario.

3.1 Numerical Model

A 2D vehicle-bridge interaction model has been used to represent vehicle-crossing events over a bridge. The vehicle consists of a 2-axle configuration represented by a 4-DOF model, where a series of spring and dashpot systems, which represent the suspension and tyre properties, connect the main vehicle mass, axle masses and road, as shown in Figure 2. The bridge is a Finite Element Model (FEM) made of 20 standard beam elements. The vehicle-bridge interaction is achieved by establishing the coupled equations of motion for each time step of the numerical integration (Newmark-β). Bridge damage is modelled as a reduction of bending stiffness in one element. This numerical model is used to obtain strain responses at three locations ($L/4, L/2, 3L/4$) along a 9 m fixed-fixed bridge for a vehicle traversing at a constant speed of 80 km/h. These signals are then corrupted with random noise that gives a signal-to-noise ratio (SNR) of 10. Additional model properties can be found in Cantero et al. (2015).

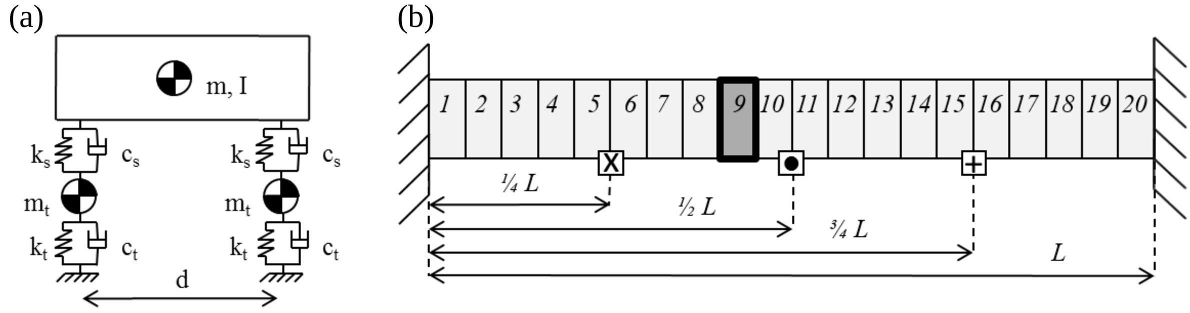

Figure 2 – Schematic Representation of Numerical Models; (a) 2-Axle Vehicle; (b) FEM Beam

3.2 Example with Damaged Bridge

The calculated bridge responses from the numerical model are the strain measurements for a multiple sensor B-WIM system. The influence lines for the undamaged bridge are obtained during calibration and are shown in Figure 3. When bridge damage is introduced, all influence lines are affected, changing in shape and magnitude. However, these changes are small, as shown in Figure 3, even for a significant damage (30% stiffness reduction near mid-span). Following the notation from Section 2, the influence lines for healthy and damaged case, correspond to $\{I_t\}$ and $\{\tilde{I}_t\}$ respectively.

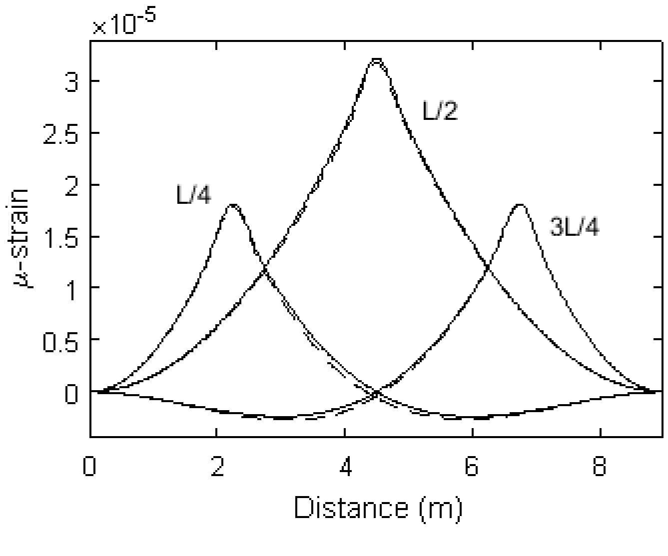

Figure 3 – Influence Lines Comparison at Various Sections for Healthy Bridge (solid) and Damaged Bridge (dashed) with 30% Bending Stiffness Reduction in Element 9.

The Virtual Axle concept can easily be applied to an existing B-WIM installation. The same information, signals and algorithm are used except for the addition of a fictitious weightless axle. Here, one particular numerical example is explored for a 2-axle vehicle crossing a healthy and a damaged bridge. The Virtual Axle idea means that the Moses algorithm is applied assuming that the vehicle has 3 axles, instead of two. As a result, 3 axle weight estimates are obtained. Under ideal conditions (healthy bridge, no dynamics and no noise) the estimated weight for the third axle is zero, rendering non-zero values when there has been a change in influence line shape.

The location of this additional third axis with respect to the other two is a key parameter. In fact, it can be located either in front or to the back of the vehicle. The maximum distance between the virtual axle and the vehicle is limited by the length of the influence line L, as shown theoretically in Section 2. Therefore, it is possible to obtain weight estimates for virtual axles located between $-L$ (back of vehicle) and $+L$ (front of vehicle). Figure 4 shows the VA estimates within the valid distance range, and compares the results between healthy and damaged bridges. The VA values are given as a percentage of the Gross Vehicle Weight (GVW).

An inherent limitation of the Moses algorithm is related to closely spaced axles, which renders an ill-conditioned linear system to solve. Small perturbations in the signal (e.g. noise), produce unreliable and unrealistic results. Commonly, B-WIM system can avoid this issue by grouping axles that are very close together and imposing the condition that each of the axles in the group would have the same axle weight. However, it is not possible to apply this simplification to the VA calculations. Therefore, in order to avoid ill-conditioning of the system, the location of the virtual axle is placed at a minimum distance L_0 (equal to ±10% of L) away from the vehicle. The assumed range of ill-conditioned virtual axle distances correspond to the shaded area shown in Figure 4.

Because this example includes the dynamic behaviour of the bridge and added noise to the signals, the VA results are not exactly zero even for the healthy bridge case. However, Figure 4 shows some clear differences in VA estimates between healthy and damaged cases. For the considered damage scenario, some sensors indicate larger deviations of VA results with respect to the healthy case. In particular, the sensors at L/4 and 3L/4 show a distinct variation in VA estimates, as opposed to the sensor at mid-span.

3.3 Derivation of Damage Index

The application of the VA concept gives a range of weight axle estimates that depend on the virtual axle distance to the vehicle, as shown in Figure 4. Furthermore, the obtained virtual axle values can be either positive or negative and cannot be interpreted directly. What is more, the VA results are slightly different for every truck-crossing event, because of different vehicle characteristics (number of axles, suspension properties, weight distribution ...) and traversing speed that produce different dynamic responses in the structure. Therefore, in order to facilitate the interpretation of the results from a VA analysis, a single representative value should be devised. One possibility is to consider the average for either front- or back-VA analysis. This indicator is termed here Damage Index (DI), because its value is related to changes in structure's influence, and is formally defined in Equation 3.

$$DI = \frac{\int_{L_0}^{L} VA\, d(d_{VA})}{L - L_0} \qquad \text{Eq. (3)}$$

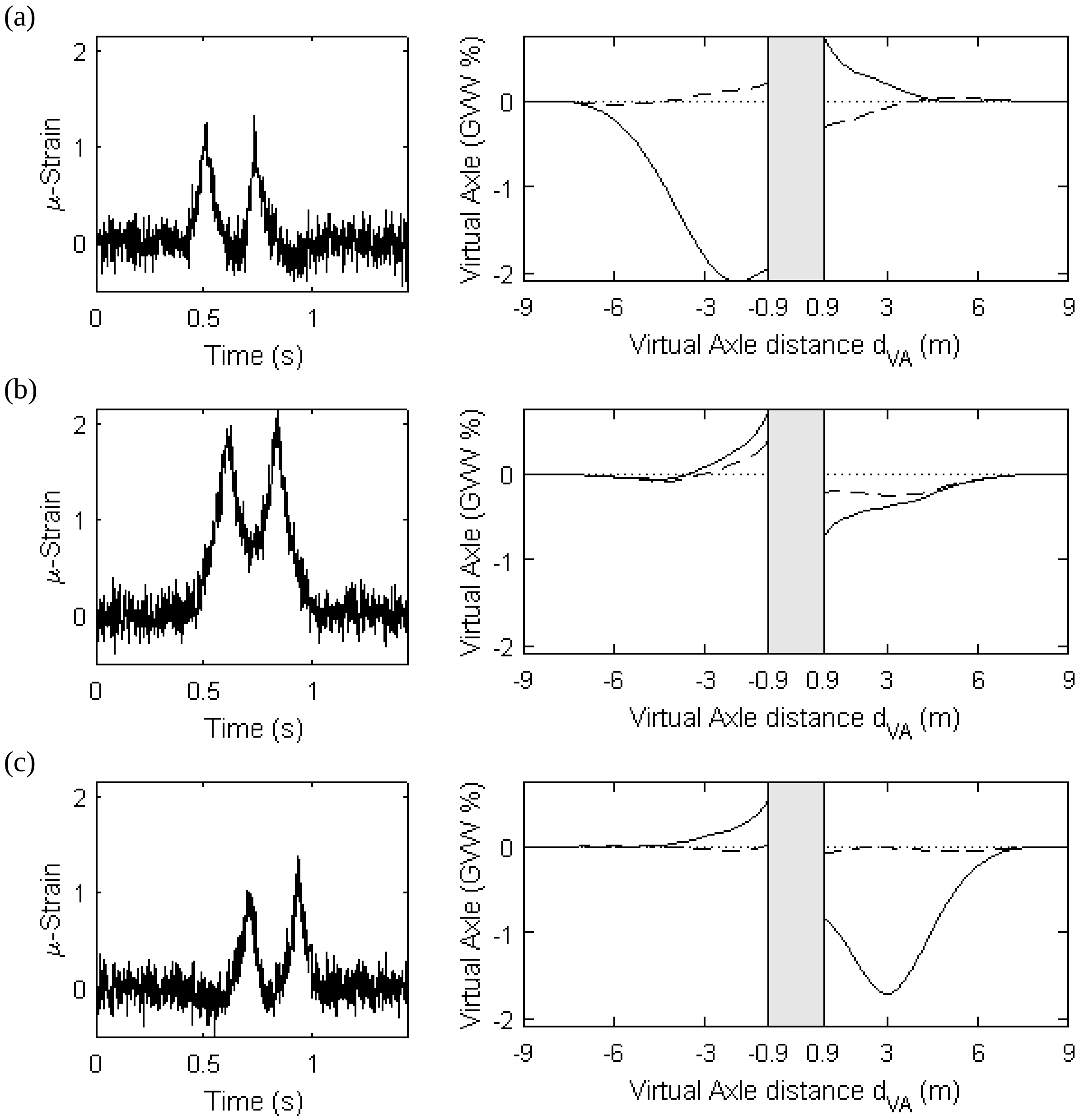

Figure 4 – Left: Strain Signals for a Vehicle-Crossing Event. Right: Virtual Axle Results for Healthy (dashed) and Damaged (solid) Bridge. Sensor Location: (a) 1/4 Span; (b) 1/2 Span; (c) 3/4 Span.

4. Parametric Study with Monte Carlo

The VA axle method and the damage index (DI) presented in previous sections are tested numerically to explore their applicability to more realistic scenarios. To that end, a Monte Carlo analysis was performed, in which 2-axle vehicle crossing events are simulated with randomly sampled vehicle properties. Normally distributed values are taken, amongst others, for vehicle speed, suspension properties and mass distribution. See Cantero et al. (2015) for further details. The performance of the DI index is evaluated for different bridge damage magnitudes and damage locations in separate subsections.

4.1 Influence of Damage Magnitude

Figure 5 shows the mean and standard deviation results from the Monte Carlo analysis, considering a bridge with damage near mid-span and damage magnitude varying from healthy (0%) to 30% stiffness reduction in increments of 0.5%. Each dot in Figure 5 represents the mean result of 200 randomly sampled vehicle events. Additionally, different sub-figures are shown for either front- or back-VA analysis, as well as for three sensor locations on the bridge. The results clearly show that the DI derived from VA analysis is sensitive to the damage magnitude. However, not all sensors are equally sensitive for a damage near mid-span. It is also interesting to see that there is some indication of symmetry within the results. For instance, the back-VA results at L/4 (left Figure 5a) are similar to the front-VA results at 3L/4 (right Figure 5c).

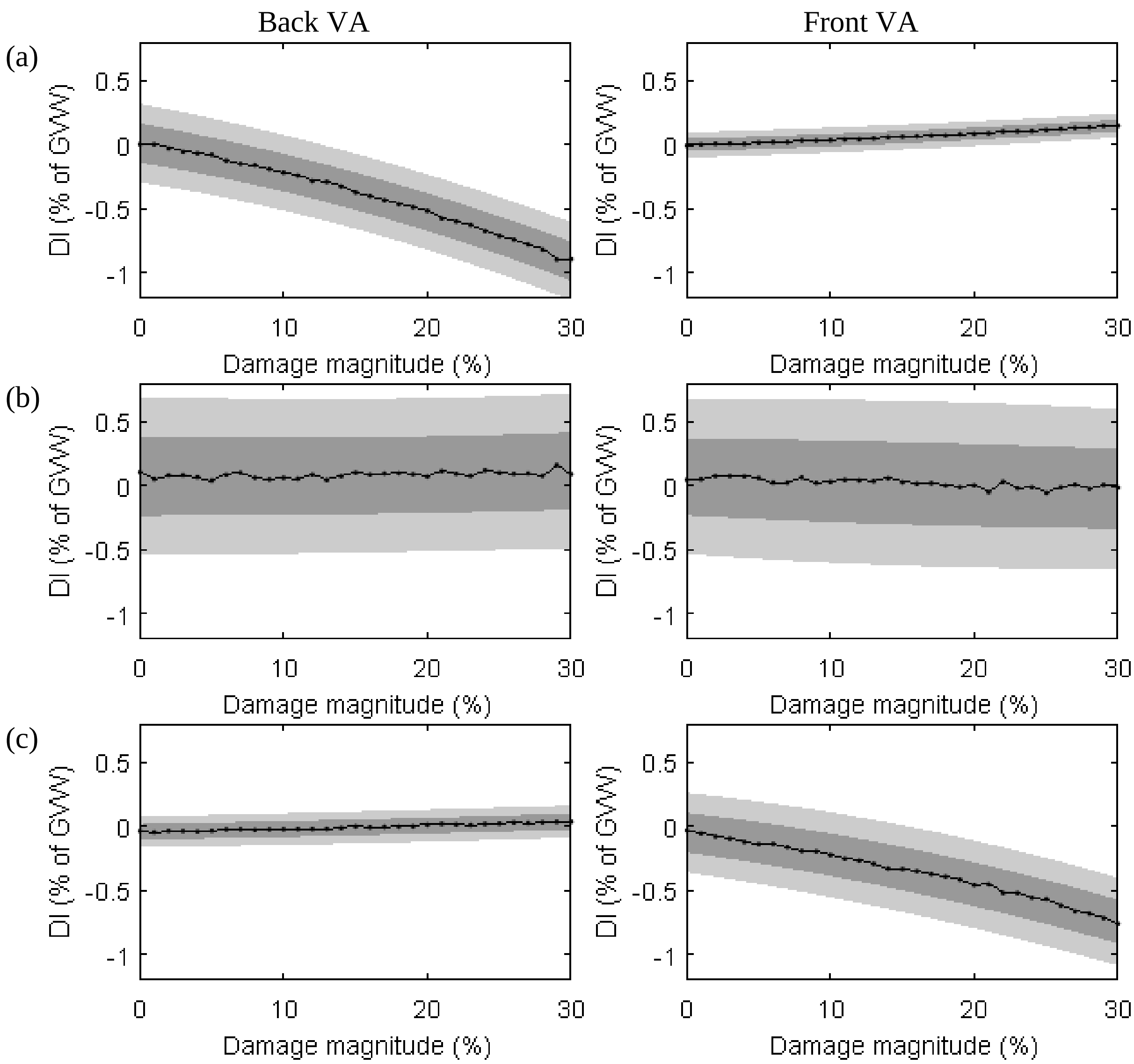

Figure 5 – Influence of Damage Magnitude. Mean DI (solid-dotted line), $\pm\sigma$ (dark shaded), $\pm 2\sigma$ (light shaded). For B-WIM Sensor Locations: (a) 1/4 Span; (b) 1/2 Span; (c) 3/4 Span.

4.2 Influence of Damage Location

Similar to previous section, Figure 6 shows results from a Monte Carlo analysis but in this occasion, the damage magnitude is fixed (30%), whereas the damage location is varied along the bridge. The analysis of the average DI values shows large sensitivity variations between sensors and type of analysis (front- compared to back-VA). The highest sensitivities are found for damages located near the supports when analysing the signals from the closest sensor to that damage. For instance, a damage near the right support could be detected when performing the front-VA analysis of the sensor located at 3L/4 (right Figure 6c).

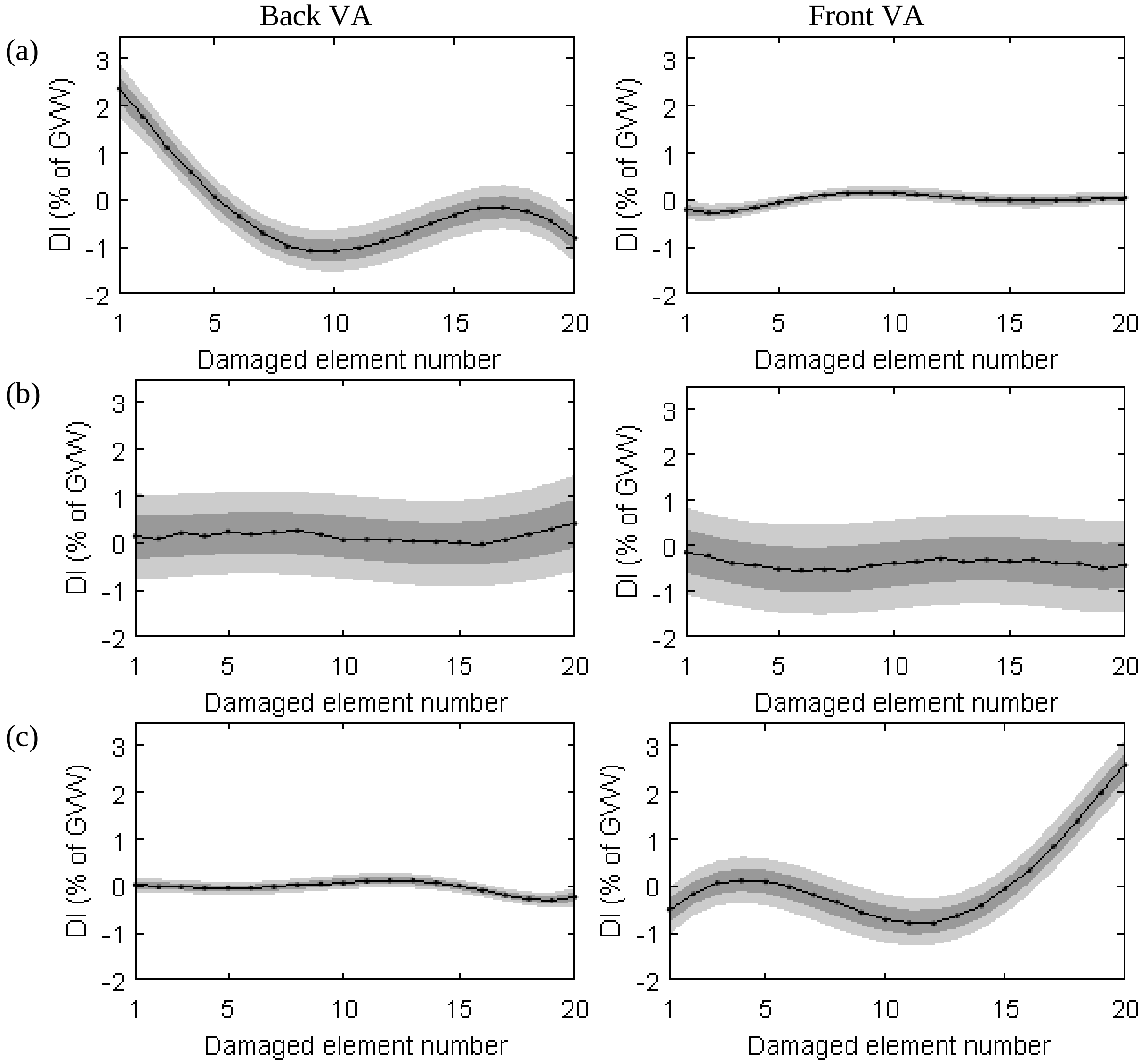

Figure 6 - Influence of Damage Location. Mean DI (solid-dotted line), $\pm\sigma$ (dark shaded), $\pm 2\sigma$ (light shaded). For B-WIM Sensor Locations: (a) 1/4 Span; (b) 1/2 Span; (c) 3/4 Span.

5. Discussion and Conclusion

This paper has provided a qualitative description of the Virtual Axle concept. This novel idea can readily be tested on existing B-WIM installations since it does not require any physical modification. To apply the VA concept, only modifications on the calculation algorithm are required.

Section 2 also listed the most important properties of VA concept. Because of these properties, the applicability of the VA idea is limited to situations where a change in shape of the influence line has occurred. This is the case when local damage occurs in statically indeterminate structures; for instance, single span bridges with rigid or semi-rigid supports, portal frames and multiple-span continuous bridges.

Section 3 has shown the application of the VA concept to one particular numerical example. Due to the range of possible virtual axle distances that can be considered, the method renders an array of results. A damage index is defined to facilitate the use of this method to detect bridge damage. However, it is acknowledged that it is possible to specify alternative definitions for a damage index, which might improve the results presented in here.

Finally, the parametric study in Section 4 has shown that VA and its related DI are sensitive to bridge damage. The numerical results show, that the sensitivity of the proposed method is good enough to compensate for the variability in results due to: difference in vehicle properties, bridge dynamics and signal noise. Therefore, the method could be classified as a Level I SHM technique. The VA methodology could also provide some indication on damage location.

This paper presents the VA concept and shows that it can readily be tested on existing B-WIM systems. The numerical results have shown its potential use for SHM of bridges. However, the practical applicability of the method has not been tested on measured signals from a real bridge. In a real-case scenario, the proposed method is faced with the challenge of changing environmental conditions as well as possible insufficient sensitivity to detect small or moderate damages. Furthermore, the sensitivity is strongly dependent on the damage location and sensor location. Therefore, further work is required to explore the potential of the VA concept under operational conditions.

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EFFECTIVENESS OF THE CORRELATION APPROACH FOR DETERMINATION OF VEHICLE VELOCITY ON REAL WORLD NOR-BWIM DATA




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Abstract

BWIM systems can give valuable information regarding real traffic, providing data for traffic analysis and assessment of structural conditions of the bridge itself. In the NOR-BWIM approach, strains caused by passing vehicles are measured by specialized sensors attached underneath the bridge slab. It allows the evaluation of number and spacing of vehicle axles, without the need of axle detectors on the road surface. However, the accuracy of axle detection and speed estimation may diminish. In order to improve these estimates, cross-correlation of FAD signals is an approach that could be applied. This paper verifies the applicability of cross-correlation of both filtered and unfiltered signals, related to real world data from two bridges in Brazil. The filtered cross-correlation technique shows accurate predictions for vehicle velocity even where FAD peaks are difficult to be identified.

Keywords: NOR-BWIM, Free-of-axle, Cross-correlation, Filtering, Velocity estimate, Real data.

Résumé

La pesage en marche par pont instrumenté (BWIM) peut fournir des informations précieuses sur les véhicules qui circulent sur les routes. En effet, le BWIM fournit des données pour l'analyse du trafic et l'évaluation des charges afin de mesurer la déformation de la structure et le nombre d'essieux des véhicules. Il est possible d'éviter les capteurs de détection d'essieux sur la surface du pont en utilisant des capteurs spécialisés sous le pont. Lors de l'utilisation de tels capteurs, la précision de la détection d'essieu et l'estimation de la vitesse peuvent diminuer. La corrélation croisée des signaux FAD est l'une des approches utilisées, qui peut être appliquée à des signaux filtrés ou non filtrés. Cet article vérifie l'applicabilité de la corrélation avec les deux procédures sur des signaux mesurés sur des ponts au Brésil. La technique de corrélation filtrée montre une amélioration remarquable de la vitesse estimée tout en évitant de perturber le signal des ponts dont les pics sont plus clairement identifiés.

Mots-clés: NOR-BWIM, Free-of-axle, Corrélation croisée, Filtering, Velocity estimate, Real data.

1. Introduction

Bridge Weigh in Motion (B-WIM) uses measured strain resulting of passing vehicles in order to determine actual traffic loading. Additionally, the number and spacing of axles of such vehicles are necessary for performing the weighing procedure and speed estimate. Following the nothing-on-road (NOR) BWIM methodology it is possible to avoid the use of sensors on the road surface, which often cause disruption in the traffic and have lower durability (He et al. 2016). Znidaric, Kalin, and Lavric (2002) developed a free-of-axle detector (FAD) method that consists on the use of sensors located beneath the bridge slab, where peaks in the resulting signals indicate the passage of a vehicle axle. FAD sensors are useful for both determining the axle distribution of passing vehicles as well as their velocity.

In order to estimate the velocity of the passing vehicle, it is necessary calculating the delay between the peaks indicated between longitudinally spaced FAD sensors. With this delay and the known distance between FAD sensors, an estimated velocity can be obtained. Although this may appear a simple task, measurements are usually corrupted with some kind of noise (Zhu and Law 2016). Therefore, signals often present peaks that are not related to the axle passage itself. This situation can disturb both weighing and influence line acquisition, since a reliable definition of FAD peaks is necessary in order to calculate the velocity, which is then required for further analyses (Zhao and Uddin 2010). Thus, the determination of vehicle velocity is one key feature that could affect the results as a whole (Lansdell, Song, and Dixon 2017).

Considering the uncertainty regarding the source of FAD peaks, one must take into account that the peak found might not correspond to the passage of an axle directly above the sensor. An approach applied to overcome this issue is taking the cross-correlation of the measurements of each FAD sensor, associating the value of the delay between each signal to the one that results in the maximum correlation (Kalin, Žnidarič, and Lavrič 2006). With this idea, it is possible to estimate the velocity without the need of finding signal peaks. Some authors have reported good results in applying this procedure to real data (Junges, Pinto, and Miguel 2017; Kolev 2015; OBrien and Žnidarič 2001).

Despite the fact that this technique may result in predicted velocities in good agreement with the expected result, the FAD signal provided by each sensor can have considerably distinct shapes when comparing different bridges (Kalin, Žnidarič, and Lavrič 2006). In such cases, the correlation value could not represent the real delay between passing axles and, consequently, results are not reasonable for speed estimates. To avoid this effect Kalin, Žnidarič, and Lavrič (2006) proposed a filtering technique that is supposed to result in more robust estimates of velocity. Although the authors argued about the robustness of their method, there is no detailed analysis about the speed prediction.

In order to assess the robustness of different approaches for velocity estimate, in this study the cross-correlation of FAD signals, for both filtered and unfiltered signals, is compared with the value obtained by calculating delay directly from measurement peaks. Data collected from two distinct bridges, based on passage of vehicles with three and five axles, are analyzed. The aim of this paper is to discuss the suitability of each procedure.

In section two, the basis of the correlation and filtering approaches are presented. Section three discusses the experimental procedure used for analysis, mainly regarding the characteristics of the bridges where the methods were employed. In section four, comparison results are presented and in section five concluding remarks are drawn.

2. Procedures description

The cross-correlation is a measure of similarity of signals. Considering the data from two FAD sensors, located longitudinally apart, the time delay between each consecutive peak of the signal represent the time needed for each axle of the vehicle to move from the location of one sensor to the other. Knowing this value and the distance between sensors, it is possible to calculate the velocity of the vehicle. The cross-correlation can be computed by the following integral:

$$(f \star g)(\tau) \overset{\text{def}}{=} \int_{-\infty}^{\infty} f(t)g(t+\tau)dt, \tag{1}$$

where f and g represent the FAD signals from sensors at two longitudinal locations and τ represents the delay between signals.

Moreover, for the BWIM application, considering the non-continuous data acquisition of the system, the discrete form of this integral is considered:

$$(f \star g)[\tau] \overset{\text{def}}{=} \sum_{m=-\infty}^{\infty} f[m]\, g[m+\tau]. \tag{2}$$

Suppose that the FAD response is the same for two sensors, which is the case only in the ideal situation, without noise. The shift-parameter $\boldsymbol{\tau}$ that maximizes the integral of the product of both signals will correspond to the effective time delay between axle passages. Thus, the premise here is that both signals will be almost identical but time-shifted versions of each other. It could be observed in Figure 1, where both the signal as a function of time and the time-shifted version used to calculate the delay are shown.

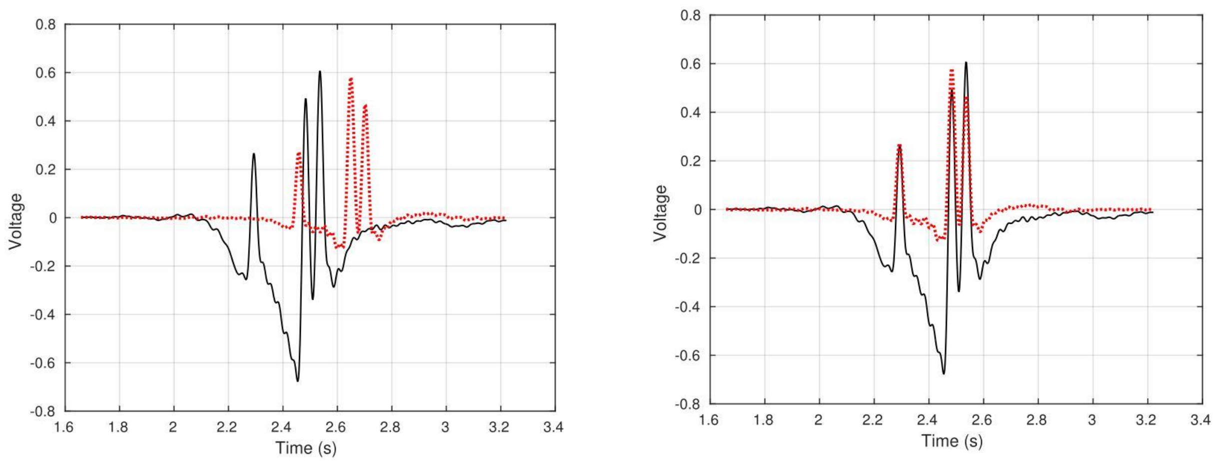

Figure 1 – Example of measured signal (left) and shift signal (right)

Although this approach seems to be suitable for speed estimation, some signal shapes may be problematic, such as in presence of high dynamic bridge response or measurement noise. In this context, the operation of cross-correlation of measured FAD signals could result in unacceptable values. In order to overcome this issue, filtering of the measured FAD signal arises as an alternative. If correctly applied, the filter is able to eliminate undesired information that is usually present on data, improving the correspondent speed calculation.

There are many kinds of filters that could be applied for processing time domain signals. Among these, moving average is applied in this study. This is one of the most common filters in signal processing, mainly because it is the easiest digital filter to understand and use. Despite its simplicity, it shows very good results for many applications (Smith 2013). It is calculated by the following expression:

$$\overline{f}(T) = \frac{1}{2N+1} \sum_{i=-N}^{N} f(T+i), \tag{3}$$

where $f(T)$ and $\overline{f}(T)$ are the original and filtered signal, respectively. Furthermore, N is the number of neighbor points employed. Indeed, the value of filtered signal in one ordinate is the average of their neighbors, counting N values from each side, justifying the name of the filter.

The filtering procedure analyzed follows the work of Kalin, Žnidarič, and Lavrič (2006). The main objective of this idea was to better represent groups of close axles, since it could result in shapes whose individual peaks are difficult to be identified. The FAD signal was filtered twice, using different filter lengths of 0.6 and 1.6 meters, values related to the lower and upper bounds of the length usually encountered for groups of axles. Both filtered signals were then subtracted, resulting in band-pass effect.

It is worth to mention that for using the moving average filter, it is necessary setting only one parameter, which can be directly obtained by the filter lengths previously defined. Thus, applying this filtering technique prevents conclusions from being corrupted by user dependent parameters.

3. Bridges description

Two distinct bridges are analyzed in the present study, the Lambari and Itinguijada bridges, both located in the city of Uruaçu, Brazil. The individual aspects of the experimental procedure for each case, related to both main bridge dimensions and vehicles used in analysis, are discussed as follows.

3.1 Lambari bridge

A picture of the first bridge analyzed is presented in Figure 2. The structure is composed by four girders and five crossbeams, with a total length of 22.5 m. Figures Figure 3 and Figure 4 show the main dimensions of the cross section and the lateral view, respectively. One FAD sensor was installed in the middle span of the bridge, while the other was 4 meters longitudinally spaced from the first. Two trucks were employed for this study, with three and five axles. A total of 54 independent truck passage events were generated, 27 for each type of truck.

Figure 2 - Lambari bridge

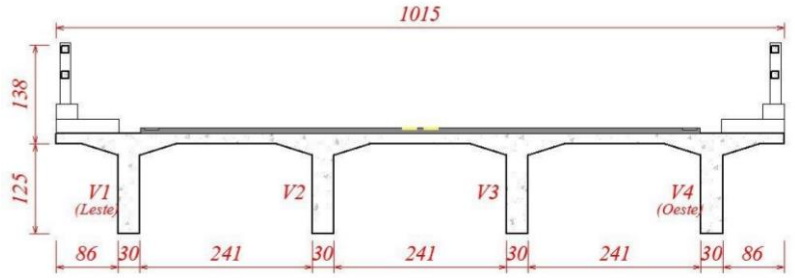

Figure 3- Middle span cross section dimensions of Lambari bridge

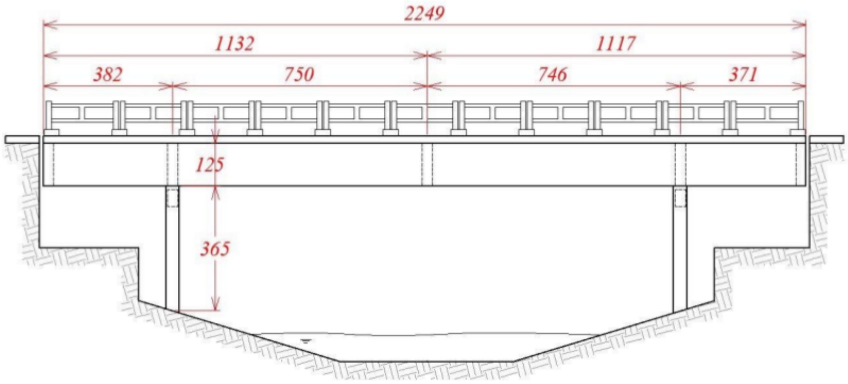

Figure 4 - Lateral view dimensions of Lambari bridge

3.2 Itinguijada bridge

The Itinguijada bridge is shown in Figure 5. The structure is composed by two girders and five cross beams, with a total length of 29.0 m. Figures Figure 6 and Figure 7 show the main dimensions of the cross section and the lateral view, respectively. One FAD sensor was installed in the middle span of the bridge, while the other was 4 meters longitudinally spaced from the first. Two trucks were employed for this study, with three and five axles. A total of 80 independent truck passage events were generated, 40 for each type of truck.

Figure 5 - Itinguijada bridge

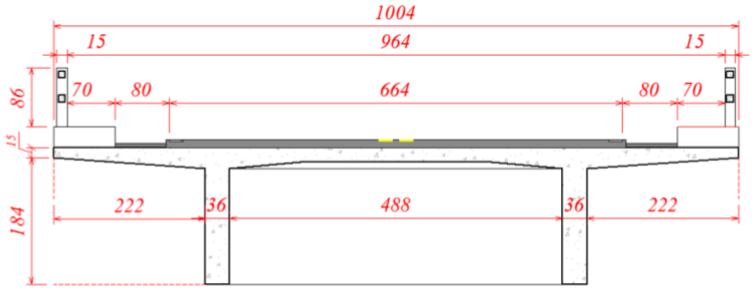

Figure 6 - Middle span cross section dimensions of Itinguijada bridge

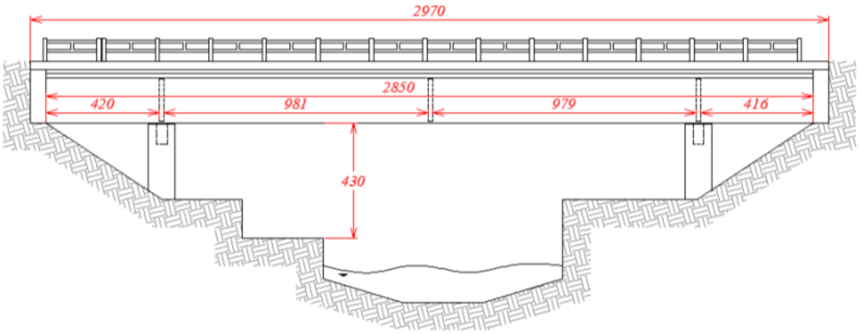

Figure 7 - Lateral view dimensions of Itinguijada bridge

4. Results

For both bridges, data corresponding to 80 events for Itinguijada and 54 for Lambari, half for each type of vehicle, was analyzed. The first point to mention is related to the shape of FAD signals originated from each bridge. A characteristic behavior is noticed for data generated at the same bridge, despite quite distinct shapes occur otherwise. In order to illustrate the observed behavior, **Erreur ! Source du renvoi introuvable.** shows the unfiltered signal of one event for each case. As could be seen, the shape of Lambari signal is quite sharpened. This characteristic is favorable to the velocity calculation procedure, since it clearly distinguishes the passage of each axle over the FAD sensor from peaks originated by noise. The signal of Itinguijada, however, is not so clear, presenting more pronounced noisy peaks. Furthermore, close axles lead to peaks that could be confused with each other, resulting in a signal whose mass of information is dispersed around these peaks. This fact indicates that velocity estimation using FAD sensors in Itinguijada might be problematic.

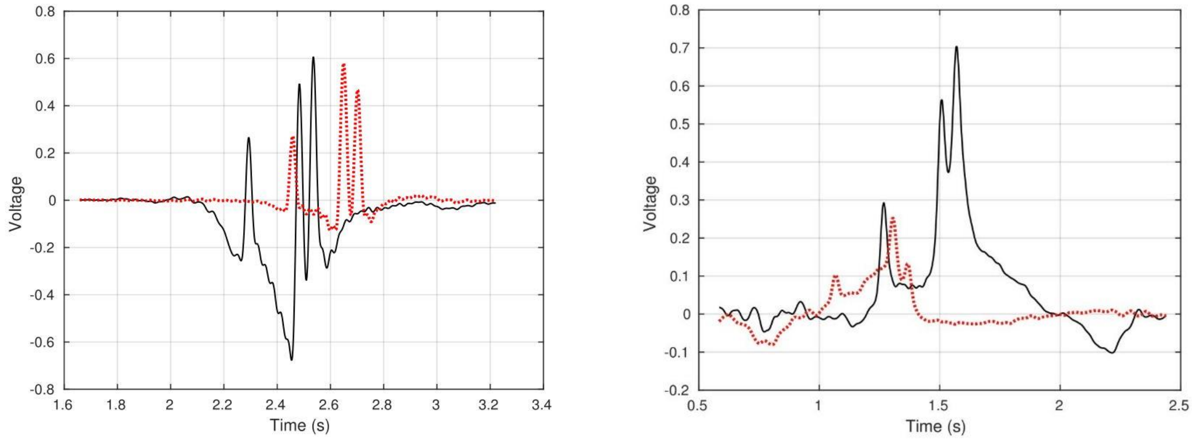

Figure 8 – Measured signal for Lambari (left) and Itinguijada (right) bridges

The speed calculated based on the cross-correlation of FAD measurements is compared with the value obtained by examining the distance between peaks from these signals. For each event, the error calculated is related to the absolute relative difference between each approach, taking the second approach as reference. Furthermore, the comparison is made by evaluating both filtered and unfiltered signals. Table 1 shows some statistics of the obtained errors, for each bridge individually.

Table 1- Results comparison of each approach by bridge

	Lambari		Itinguijada	
	Unfiltered	Filtered	Unfiltered	Filtered
Number of events	54	54	80	80
Max absolute diff. (%)	2.53	2.26	51.42	2.88
Mean absolute diff. (%)	1.49	1.08	12.77	0.98
Std. absolute diff. (%)	0.46	0.57	12.42	0.67
Events with error higher than 5%	0	0	53	0
Events with error higher than 10%	0	0	28	0

The first point to highlight here is the large difference among the results by bridge without filtering, in all statistics. Specially, it could be noticed that for Lambari, there were no events where error value overcomes the threshold of 5%, while in Itinguijada this occurred on more than a half of events. Moreover, events with more than 50% of error could be observed. For one event, the resulting velocity estimate was of 90 km/h for a truck passing at 60km/h. The main reason for this poor performance was that when performing the cross-correlation of the FAD measured response, an effect of summing up contributions of regions other than the peak itself was observed. Therefore, the achieved value of delay and, consequently, velocity was corrupted by this misleading mass of signal around the peak. Although this increased estimation difficulty in Itinguijada was already expected, the magnitude observed was quite impressive.

When analyzing the filtered and unfiltered approaches, two important aspects should be pointed. Firstly, the filtered signal of Itinguijada was able to estimate velocities as close to the real value as those observed in Lambari. Therefore, the procedure of filtering was able to make the FAD measurements suitable for speed prediction in Itinguijada. Secondly, the filtering procedure has not altered the good agreement of values calculated for Lambari. Thus, the filtering technique actually resulted in a more robust approach, able to deal with both bridges, despite signals having remarkably distinct shapes.

In order to understand this effect, it is interesting to focus on the shape of filtered signal generated by FAD sensors in both bridges. **Erreur ! Source du renvoi introuvable.** presents one example of filtered event from Lambari and Itinguijada bridges, respectively. Although the filtered signal seems to possess increased high frequency noise when compared to the unfiltered one, the peaks seems more pronounced. Thus, the cross-correlation operation spread out the noisy contribution and focus on the delay where the peaks match with each other. This effect can be clearly observed when analyzing the value of cross-correlation as a function of the corresponding delay, as shown in Figures **Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.** for one event of Lambari and another for Itinguijada, respectively.

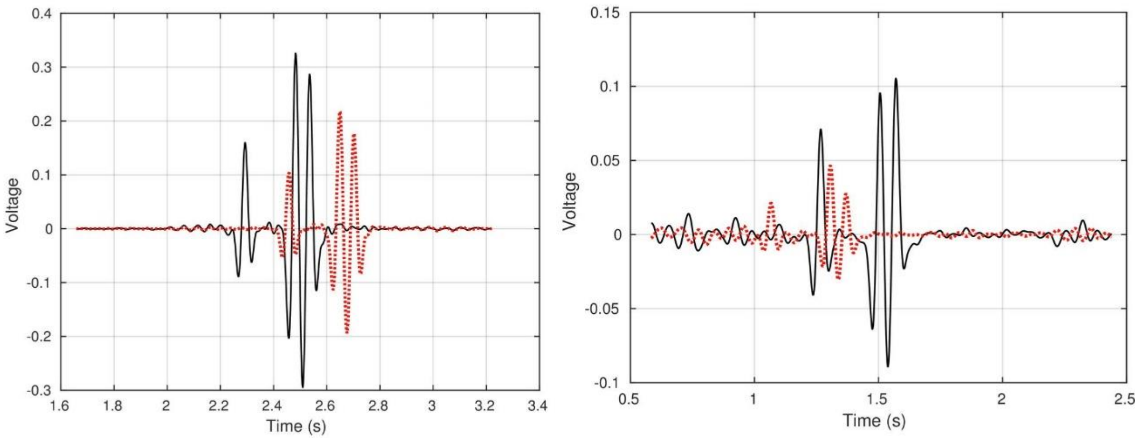

Figure 9 – Example events of filtered signals for Lambari (left) and Itinguijada (right) bridges

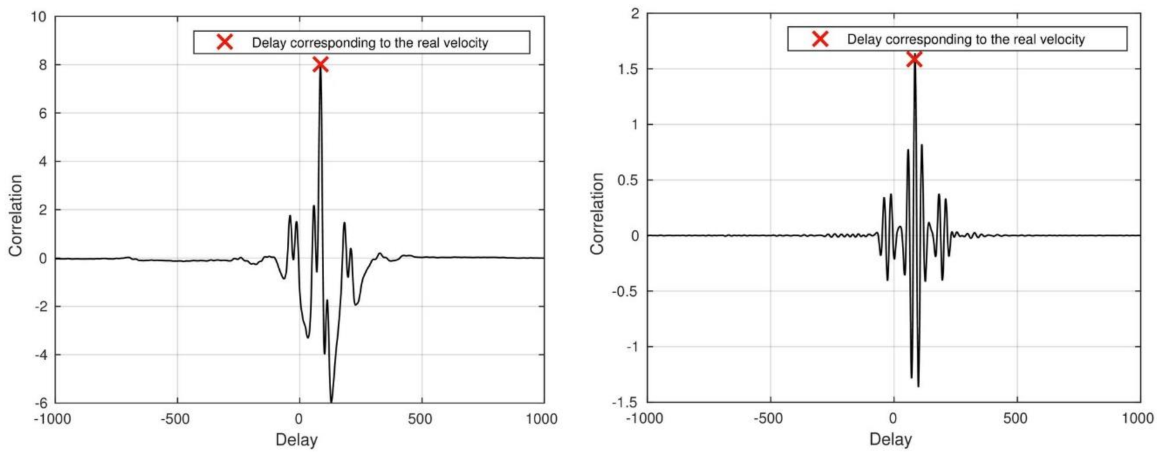

Figure 10 – Comparison among correlation in unfiltered (left) and filtered (right) events for Lambari bridge

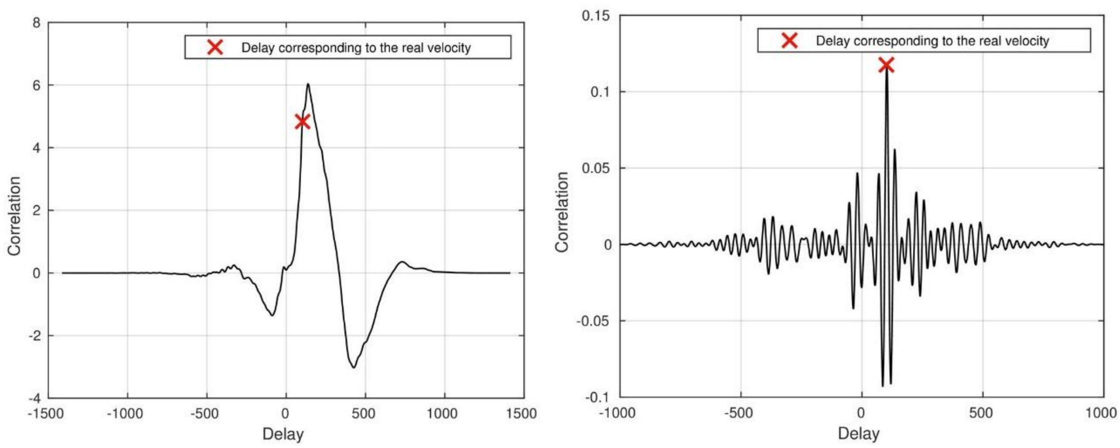

Figure 11 – Comparison among correlation in unfiltered (left) and filtered (right) events for Itinguijada bridge

The difference between cross-correlation in unfiltered signals is remarkable. While in Lambari data a maximum value that is well above all the others occurs, in Itinguijada a region of high maximum value is observed. This fact can lead to miscalculations, associating the estimated delay to a situation other than the coincidence of the peaks. This is observable in **Erreur ! Source du renvoi introuvable.**a, where the maximum value does not match with the expected value based on the real velocity of the truck. However, when the signal is filtered, sharpened peaks for both bridges can be observed. Therefore, the process of filtering is able to turn the measurement of Itinguijada suitable to application of cross-correlation at the same time that the Lambari data remains with good agreement. As this situation is noticeable for all events and for both bridges, the combined approach of filtering and cross-correlation of signals is regarded as quite robust.

5. Conclusions

This study aimed at evaluating the effect of the use of cross-correlation on FAD sensors for estimating vehicle velocity in NOR-BWIM systems. Although the evident advantages of using the sensors beneath the bridge and the fact that the cross-correlation approach behaves well when applied to simulated signals, structural characteristics of real bridges as well as dynamic and intrinsic noise of the process may lead to inaccurate estimates. Thus, extra techniques such as filtering procedures may be employed in order to disambiguate the effect of group of axles and better emphasize peaks. Results of the estimated velocity have shown major improvement especially for Itinguijada, the second bridge studied, when considering the filtering approach. The effect of filtering has not negatively perturbed the results for the bridge where peaks were already easily identified, thus it was regarded as a robust and useful technique to be applied prior to the velocity estimation.

6. Acknowledgements

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BRIDGE WEIGH-IN-MOTION (B-WIM) AS THE MAIN TOOL FOR ISSUING SPECIAL TRAFFIC AUTHORIZATIONS (AETs) IN BRAZIL





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Abstract

In Brazil, according to the National Department of Transport Infrastructure (DNIT), special vehicles transporting indivisible loads and overweight and/or oversize vehicles need a Special Traffic Authorization (AET) for use federal highways. This requires a structure feasibility study (geometry and load capacity) for the bridges along the highway. The methodology used in this research is based on the bridge weigh-in-motion (B-WIM) system widely used in Europe. Along two years, bridges were instrumented for collecting data and analyzing their safety. Sixty sensors were installed to obtain signals produced by vehicles crossing the bridges, giving as results the Gross Vehicle Weight (GVW), weight per axis, type of vehicle and speed. By monitoring the bridges, it was possible to obtain the relationship between the GVW and the Dynamic Amplification Factor (DAF), that allow to assess the safety level for each structure (RF). If RF > 1.0 then an AET may be issued. In the present study, two special vehicles required an AET, and the RF values obtained were 3.44 and 3.30. Therefore, in both cases, the structures were shown to be safe, allowing the crossing of vehicles with special loads.

Keywords: B-WIM, weight sensor, data collecting, indivisible loads, AET.

Resumen

En Brasil, de acuerdo con el Departamento Nacional de Infraestructura de Transporte (DNIT), los vehículos especiales que transportan cargas indivisibles y vehículos con sobrepeso y / o de gran tamaño, necesitan una Autorización Especial de Tránsito (AET) para el uso de carreteras nacionales. Esto requiere un estudio de factibilidad de la estructura (geometría y capacidad de carga) de los puentes a lo largo de la carretera. La metodología utilizada en esta investigación se basa en el sistema bridge weigh-in-motion (B-WIM) ampliamente utilizado en Europa. Durante dos años, los puentes fueron instrumentados para recolectar datos y analizar su seguridad. Sesenta sensores fueron instalados para obtener señales producidas por los vehículos que cruzan los puentes, dando como resultado el peso bruto dos vehículos (GVW), el peso por eje, el tipo de vehículo y la velocidad. Al monitorear los puentes, fue posible obtener la relación entre el GVW y el Factor de Amplificación Dinámica (DAF), que permite evaluar el nivel de seguridad para cada estructura (RF). Si RF > 1.0 entonces se puede emitir una AET. En el presente estudio, dos vehículos especiales requirieron una AET, y los valores de RF obtenidos fueron 3.44 y 3.30. Por lo tanto, en ambos casos, las estructuras se mostraron seguras, permitiendo el cruce de vehículos con cargas especiales.

Mots-clés: B-WIM, sensor de peso, recolección de datos, cargas indivisibles, AET.

1. Introduction

The bridge weigh-in-motion (B-WIM) concept was introduced by Moses (1979) in the late 1970s by means of an algorithm named after him. Studies only gained international visibility in the early 1990s, when researchers from Slovenia and Ireland developed prototypes using Moses's methodology. By the end of the decade, several European research projects on the B-WIM system were released (Žnidarič and Kulauzović, 2018).

The Moses (1979) algorithm has been modified in the commercial systems, but it presents the basic theoretical principle of the Line of Influence (IL) concept to obtain the weight of vehicles crossing a bridge. In Brazil, the B-WIM system was first used in 2008 and the first installation in the Santa Catarina state of data collecting devices on a bridge, happened in 2012.

One of the technical responsibilities of the National Infrastructure and Transport Department (Departamento Nacional de Infraestrutura de Transportes - DNIT) of Brazil is to evaluate the safety conditions of infrastructures such as bridges, which require the issuing of Special Transit Authorization (Autorizações Especiais de Trânsito – AET) documents. These are issued to special load or indivisible load vehicles that do not follow dimensions and weight limits established in the National norms (Conselho Nacional de Trânsito - CONTRAN).

The majority of Brazilian bridges were built in the 1960s, thus constant monitoring and deep analysis of structural conditions are required to guarantee the safety of users and of the structure itself. In this scenario, B-WIM technology can be an important ally, as it can measure the impact of dynamic forces over the structure in a nondestructive way and retrieve relevant data for the analysis of infrastructure constructions. The installation of strain sensors and data collectors on the bridge can provide information such as speed, distance between axes, weight per axes, vehicle category and Gross Vehicle Weight (GVW).

The B-WIM system presents advantages for use and dissemination as per the studies of Žnidarič & Lavrič (2010) qtd. in Žnidarič et al. (2016), pioneers in this type of technology. These systems include high precision data retrieved from uniform surfaces and reasonably accurate information from non-uniform surfaces. Ease of installation of devices with no obstruction to the road, access to structural information of the bridges and portability of equipment without reducing accuracy, are positive aspects of the system. The authors describe the cases for the use of this type of technology, such as the choice of a bridge that allows for the proper calibration to be installed. However, it is important knowledge of how bridges work to evaluate if the system is properly configured.

This paper presents the Brazilian methodology of bridge inspection and safety assessment that will contribute to the issuing of AET using B-WIM technology.

2. B-WIM in Brazil

With the advance of WIM technologies for road networks, the first test of Weigh-in-Motion on bridges took place in 2012 in Palhoça city, in Santa Catarina state. The bridge in this study has a seven prefabricated prestressed concrete longitudinal beam structure with a concrete deck. The bridge was instrumented with sixteen strains sensors, including a weighing sensor applied on each of the seven longitudinal beam spans (WM), four Free-of-df detectors (FAD), and five sensors for shear stress distribution detection near the beam's support (WC), as shown on Figure 1. The system was calibrated using two vehicles: a rigid three-axle truck and a six-axle articulated truck (semi-trailer), with thirteen crossings on each lane carried out for each truck (ZAG, 2012).

Figure 1 - General view of the installation (left) and weight sensors (WM), shear stress (WC) and Free-of-Axle Detectors (FAD) sensors (right).

Shortly after, three bridges were instrumented in the state of Goiás, center west region of Brazil, with a research focus, of which the collected data is now used in this paper.

3. Instrumentation and Data Collection with B-WIM

This study aims to present the installations and data retrieved from the application of B-WIM methodology to inspect and evaluate three bridges during a two-year research period. The instrumentations and readings took place on the bridges that cross the Passa Três River, the Itinguijada River, and the Lambari River along the federal highway BR-153 at the 197th km, 147th km, and 135th km, respectively.

A visual inspection was completed prior to the installation of the weighing sensors, to evaluate the general conditions of the bridges and to identify any pathologies present. For this initial analysis, non-destructive tests such as pacometry, corrosion potential, sclerometer test, and ultrasound were used. A rating from very good to satisfactory was established, based on the deterioration factor that determines the bridge conditions to receive the instrumentation. Table 1 presents the technical data and evaluation of each bridge.

As for service conditions and structural load capacity, all bridges were in a normal state even though a few signs of pathology, like corrosions, were identified. The geral conditions were considered acceptable because the bridges receive regular maintenance and there is capacity of load redistribution.

Table 1 - Bridge data and rating

Bridge	Superstructure and Total Length (TL)	General Conditions	Rating
Passa Três River	3 spans simply supported, 5 longitudinal beams, No transversal beams. TL of 105 m	Does not present serious degradation.	Very good
Itinguijada River	1 simply supported span with cantilevers, 2 longitudinal beams, With transversal beams. TL of 29 m	Satisfactory condition (steel corrosion in transversal beams).	Satisfactory
Lambari River	1 span, 4 longitudinal beams, With transversal beams. TL of 22 m	Generalized presence of moisture (spots of steel corrosion).	Good

3.1 B-WIM Instrumentation

The instrumentation consists of implementing a fixed number of extensometers underneath the bridge's deck. These collect the reactions and deflexions generated by vehicles movements, allowing to determine the Gross Vehicle Weight (GVW, weight per wheel axis, and the type of vehicle. The positioning of the sensors should be carefully defined to obtain the most clear and representative signals. Figure 2 shows a typical installation for this method, while the number of sensors of each type varies according to the bridge.

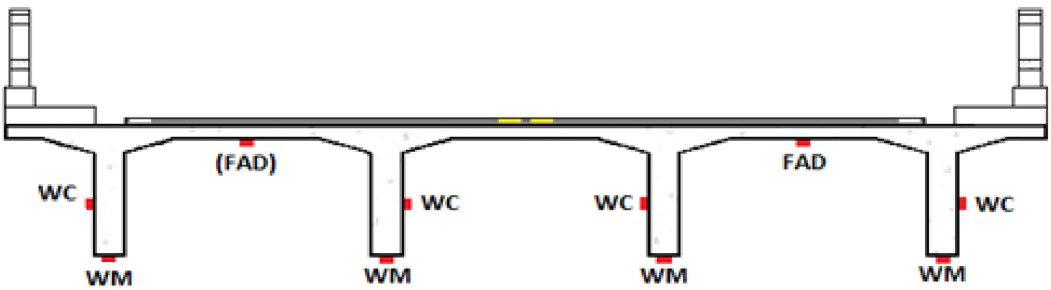

Figure 2 - B-WIM typical sensor positioning

Various types of sensors are used in the process of weighing vehicles in bridges. For the three bridges in study, as well as the bridge instrumented in Palhoça city in 2012, the WC, WM and FAD sensors were used. Table 2 summarizes the number of sensors used in each bridge being analyzed.

Table 2 - Number of sensors used in the bridges

Bridge	WC Sensors	WM Sensors	FAD Sensors
Passa Três River	10	10	4
Itinguijada River	4	4	4
Lambari River	8	8	4

3.2 System Calibration

The calibration process is the most important and sensitive stage during the installation of the monitoring system, since it is during this phase that the actual Influence Line (IL) of the bridge is obtained. This information is vital to guarantee the accuracy of the vehicle's weighing, and for the future evaluation of the bridge's safety.

For the purpose of this study, the Slovenian software SiWIM was used. According COST 323 (1999), this system uses two trucks with previously known weights in the calibration process. The calibration process consists in driving these vehicles several times over the bridge and obtaining at least ten significant readings for each type of vehicle at different speeds. As per COST 323 (1999), the recommendation for the calibration of WIM systems is that the higher the number of readings, the more precise the system will be in terms of the collected data.

The calibration of the system took into account the configuration of the structure in question, and the trucks chosen for the calibration process are amongst the most popular models on a National scale. Typically, a three-axle rigid truck and a five-axle articulated truck are chosen for the calibration. The system's calibration process was completed for all the three bridges in analysis.

3.3 B-WIM Data Collection

The B-WIM data is presented in histograms representing the quantity of vehicles weighed by the SiWIM system in relation to the GVW in tons and organized by truck type. The characterization of the traffic and the forces on each bridge varied in different stages of the analysis, the first stage being measured in 2013 and the second stage in 2017. The volume of traffic considered in the analysis refers to the majority of vehicles monitored between the two years, and the values shown on the histograms refer to each one of the bridge's lanes.

Small variations were noticed in the monitored traffic volume of each lane. The histograms on Figure 3 present the traffic characterization of analyzed bridges where (a) refers to the Passa Três River bridge, (b) Itinguijada River bridge, and (c) Lambari River bridge.

These histograms of GVW of the bridge's traffic analysis are used alongside the Influence Line (IL) to obtain the forces impacting the structure.

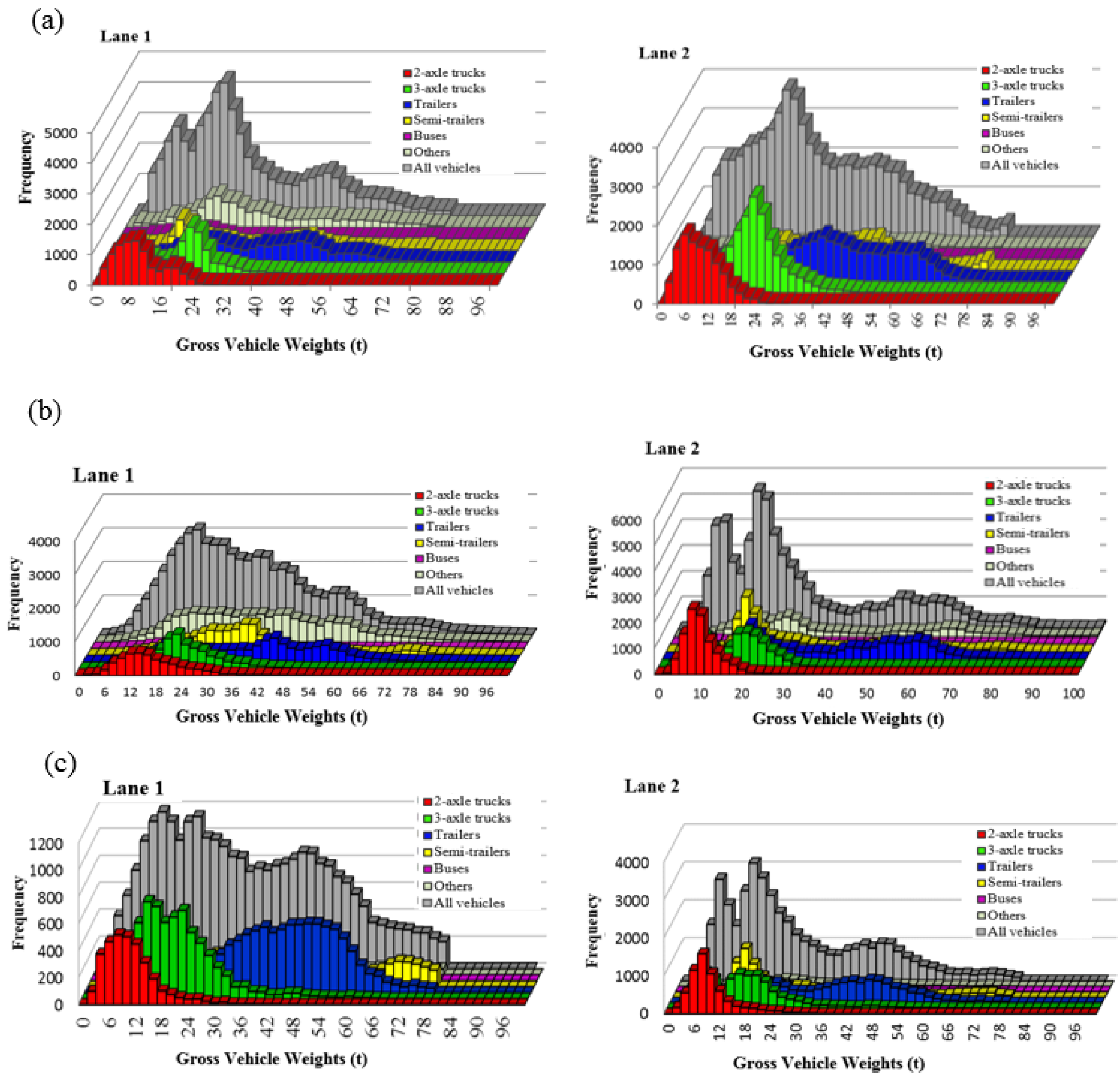

Figure 3 - Gross Vehicle Weight (GVW) histograms of the bridges

4. Safety Evaluation of the Bridges

The purpose of safety evaluation of bridge is for verify the structure's capacity to resist the loading levels that it will be subjected. In this case, the proposed methodology focuses on identifying the bridges which show levels of resistance that are close to their levels of demanding forces, thus informing the decision-making process regarding to the deployment of resources for necessary interventions (maintenance and recovery), and the confident issuing of AET permits to special vehicles that will frequently cross the bridge.

The collected data is then used in a numeric model that generates important structural characteristics such as Influence Lines (IL), traffic load distribution in different structural components, and experimental evaluation of Dynamic Amplification Factor (DAF). The B-WIM Slovenian software, which uses Eurocode or DIN 1072, was used to determine the safety levels of the bridge, that are represented by the RF factor and were obtained by Equation 1.

$$RF = \frac{\Phi \times R_d - \gamma_G \times G_n}{\gamma_Q \times G_Q \times DAF} \qquad (1)$$

Where:

Φ	Resistant capacity reduction factor obtained during the initial inspection;
Rd	Loading capacity of the beam section obtained from the structural project and site inspection;
γG, γQ	Safety factors to augment normatized forces respectively;
Gn, G_Q	Forces due to permanent loads and traffic loads, respectively, obtained from collected B-WIM data;
DAF	Dynamic Amplification Factor, obtained from collected B-WIM data.

For a bridge to be considered safe, the RF factor must be 1.0 or higher. However, special attention is advised in the consideration of values between 1.0 and 1.5.

5. Adaptation of the Methodology for Special Transport Authorization (AET)

The safety evaluation methodology can be adapted to aid in the issuing of Special Transport Authorization (AET) permits. The requirement for an AET can be seen in the structural safety evaluation context as an exceptional load of known characteristics. Effectively, when an application for an AET is filled, the necessary information of the load such as the number of wheel axes and its respective weights must be delineated. Based on the provided information, the system was adapted accordingly.

To correctly adapt the system, it is necessary to analyze the bridge's safety evaluation data from Equation 1. Through the monitoring of the bridge using the SiWIM system, it is possible to obtain the DAF of each vehicle that crosses it. The DAF values of a specific bridge are inversely proportional to the GVW of the vehicles. Therefore, the higher the GVW of the vehicle, the smaller the impact of dynamic amplification.

Figure 4 illustrates the monitoring of a bridge during a sufficient period of time to delineate a confidence curve that relates the GVW and the DAF. Thus, to identify the DAF of a special vehicle it is necessary to apply the GVW value to the equation on Figure 4. If the RF $\geq$ 1.0 then the AET can be issued as mentioned previously. If the value is lower than 1.0, then either the truck's silhouette or the transit route must be changed.

The DAF equation $DAF = 1.40 - 0.008 \times L$, where L refers to the bridge's length, were used in the bridge design code used in Slovenia before the Eurocode. Other studies developed by Žnidarič and Kulauzović (2018) presented the DAF as 1.146 in a 27 meters long bridge with six steel beams and concrete deck.

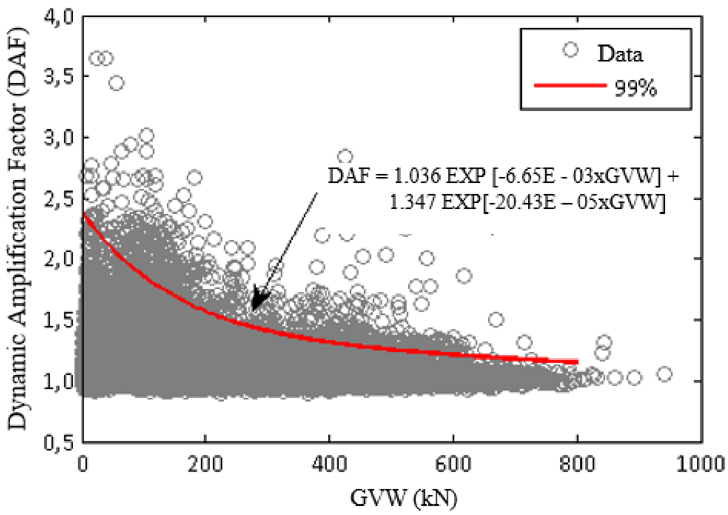

Figure 4 - DAF confidence interval for the Lambari River bridge

Using the equacion showed in Figure 4, the result values of DAF equation for the Lambari River bridge for AET release of 2 combined GVW (truck + cargo) were 1.13 and 1.10 in a 22 meters long bridge. The values, are similar with studies developed by Peaglite *et al* (2015) and says that the effects of DAF decrease as a function of increase in lenght bridge, until stability. Based on this information, this numeric model will be used to evaluate whether the bridge is able or not able to support an AET applicant vehicle.

6. Case Study

Two trucks that required a AET to drive on the highway BR-153 and that would cross the bridge over the Lambari River were verified. The bridge was monitored with the SiWIM system and the real Influence Line (IL) is illustrated in Figure 5. The relation between the DAF and the GVW was generated from the confidence curve from Figure 4 that presents values with 99% confidence that they will not be surpassed.

The first truck to pass over the bridge has a combined GVW (truck + cargo) of 69.5 tons and is distributed in 7 axles. For the issuing of an AET for trucks with a GVW less than 288 tons, the combined effect between the actual vehicle and a standard vehicle must be considered, as per the Brazilian norm NBR 7188 (2013).

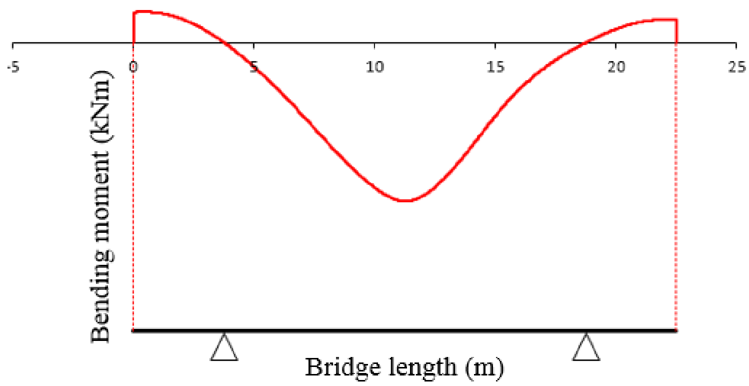

Figure 5 - Influence Line (IL) of the Lambari River bridge

The bending moment is obtained when the centre of the truck's axes is in the middle of the bridge's central span, on the LI peak, which is equal to 862.5 kNm. The normalized standard truck, when positioned in the central span, introduces a bending moment of 1,024.0 kN. Therefore, the maximum variable force (G_Q) is 1,886.5 kNm. These values are applied to the confidence interval that results in a DAF of 1.13. A summary of the calculation parameters of RF are presented in Table 3.

Table 3 - Safety parameters for the Lambari River - Truck 1

Φ	γ_G	γ_Q	G_n (kNm)	G_Q (kNm)	DAF	R_d (kNm)
0.85	1.2	1.3	1,326.3	1,886.5	1.13	4 x 3,273.0

As per Equation 1, the safety Rating Factor (RF) is 3.44, thus the AET for this truck can be issued for the GVW presented and in reference to the Lambari River bridge.

The second truck to drive through the Lambari River bridge has a combined GVW (truck + cargo) of 111.5 tons distributed along nine axles. The bending moment of this truck occurs when the centre of the axles is over the central span of the bridge, where the Influence Line peak is at 996.3 kNm. In this case, it is also necessary to combine a normalized standard truck. The maximum force G_Q is equal to 2,020.3 kNm. With this combined GVW, the DAF results in 1.10, and the parameters used can be seen in Table 4.

Table 4 - Safety Parameters for the Lambari River - Truck 2

Φ	γ_G	γ_Q	G_n (kNm)	G_Q (kNm)	DAF	R_d (kNm)
0.85	1.2	1.3	1,326.3	2,020.3	1.10	4 x 3,273.0

Since the rating factor (RF) in this case results in 3.30, this truck can also receive the AET for the presented GVW and for the Lambari River bridge.

7. Final Considerations

The road network operated by the National Department of Transport Infrastructure (DNIT) contains a significant number of bridges that require constant evaluation of the structural conditions of safety. This article summarizes the Brazilian methodology of bridge inspection and safety assessment. Considering also the load capacity of critical sections, capacity reduction factors, factor of increase of forces and permanent loads and of traffic.

In this first moment, the goal was to analyze the support capacity of the bridges and in this way the analyzes were developed according to the obtained safety factor (RF). The RF values serve as a reference for the release or not of the Special Traffic Authorization (ETA) on these bridges. During the process three bridges of the state of Goias/BR were selected. The results concerning the bridge over the Lambari River were presented and analyzed as a model.

The final considerations include the instrumentalization of these bridges, the system calibration process and the characterization of traffic and forces.
For the load, two large vehicles were used and after the requests the RF safety values were 3.44 and 3.30. Under these values, it is determined that the bridge over the Lambari River is safe and that the AET can be emitted in this stretch.

8. Acknowledments

The authors wish to thank the Departamento Nacional de Infraestrutura de Brazilian National Department of Transport Infrastructure (DNIT), specially the Road Operations Coordination (Coordenação de Operações Rodoviárias - COPERT), for their support in this research.

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Session 3 : Quality of Data and Enforcement

Chair: Jesus Leal (CEDEX, Spain)

INNOVATIVE USE OF PIEZOELECTRIC SPEED ENFORCEMENT SYSTEM FOR WEIGHT DATA COLLECTION




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Abstract

The Norwegian Public Roads Administration (NPRA) operates around 250 automatic piezoelectric traffic speed enforcement sites all over the country. The system detects the axle weights and the axle distances in addition to the velocity of the passing vehicles. However, the quality and usability of the weight data from these speed enforcement systems has been unknown and the data has not been utilized. This paper will describe a method developed for evaluating the quality of the generated weight data. The goal has been to achieve this without performing a field test for each site. The results show that the Norwegian speed enforcement system can be used for gathering statistical information about the weight distribution of heavy vehicles on many roads in Norway.

Keywords: Weigh In Motion, ITS, Weight distribution statistic

Zusammenfassung

Informationen über Gewichte und Achslasten von Fahrzeugen sind wichtige und wertvolle Informationen für Verkehrs- und Straßenplaner. Die norwegische Straßenbau Behörde Statens Vegvesen betreibt über das gesamte Land verteilt etwa 250 piezoelektrische Geschwindigkeitskontrollanlagen. Diese Anlagen messen neben der Geschwindigkeit der passierenden Fahrzeuge auch deren Achslasten und die Achsabstände. Die Datenqualität dieser Daten wurde bisher noch nicht untersucht und auch eine weitere Verwendung wurde bis dato noch nicht ins Auge gefasst. Diese Studie beschreibt die Entwicklung einer Methodik zur Qualitätskontrolle der von den Geschwindigkeitskontrollanlagen produzierten Achslast- und Abstandsdaten. Die Ergebnisse zeigen, dass das norwegische Geschwindigkeitskontrollsystem in der Tat Aufschluss über Achslastverteilungen von LKWs auf dem norwegischen Straßennetz geben kann.

Keywords: Weigh in Motion, ITS, Achslastverteilungen

1. Introduction

The Norwegian Public Roads Administration (NPRA) is interested in reliable gross weight and axle weight for heavy vehicles. Information about the amount and weight of heavy vehicles can be used for predicting road wear and for optimizing asphalt structures as well as for statistical analyses of vehicle weights. A common approach for collecting weight of vehicles is to measure their static weight at a roadside inspection site (Haugen, et al., 2016). These measurements are highly accurate. However, the procedure of stopping vehicles and checking the static weight at an inspection site is time consuming and the capacity limited (Jacob, et al., 2002).

Automatic weighing systems, which are capable of measuring the weight of moving vehicles, are a promising approach for the collection of weight data. Weigh in motion (WIM) systems are measuring the weight of an axle while it is driving over a sensor by registering the created dynamic forces (van Loo & Lees, 2015). The static weight for each passing axle is estimated from these signals. A common type of WIM sensor are piezoelectric cables. Piezoelectric cables are pressure sensitive devices that are installed in the top layer of the asphalt. Compared to other WIM installations, piezoelectric cables are relatively easy to install and less expensive (Gajda, et al., 2013).

Many countries use radar systems for speed enforcement, but the Norwegian Public Roads Administration is operating an automatic speed enforcement system based on piezoelectric cables. The system is called ‘Automatisk Trafikk Kontroll’ (ATK) in Norwegian. Around 250 ATK units are installed all over the country. Each of the sites consist of two piezoelectric cables, a camera unit and a data logger. The sensors used are Class I flat piezoceramic cables, the same sensor type used in dedicated WIM systems. The data logging unit is calculating the speed of the passing vehicles, by measuring the time for each axle of a vehicle to pass the distance of three meters between the two cables. If a passing vehicle is speeding, the camera takes a photo and a speeding ticket will be sent to the driver. Figure 1 shows two piezo cables, installed at a depth of 25 mm in the asphalt top layer and the corresponding camera unit. In addition to the velocity of the passing vehicles, the piezoelectric cables are also measuring the weight of the passing axles and the distances in-between. Since the data loggers are not optimized for weight data collection, the quality and usability of the weight data from ATK sites was unknown. The weight data has not been tested or utilized. Weight data consequently became an unused by-product from the ATK units.

Figure 1 - ATK Piezo cables and camera unit

The Norwegian Public Roads Administration started this project to evaluate, whether this data could be used for gaining statistical information about the weight distribution of heavy vehicles on the Norwegian road network. That information could be particularly useful for road and pavement design. The entire project was a close cooperation between the NPRA traffic data and pavement group. Since the piezoelectric cables used are not suitable for accurate measurement of overloads or a narrow range of heavy loads (Al-Qadi, et al., 2016), the intent of this study was to use the ATK system for monitoring of average truck loads and weight distributions on the Norwegian road network. Given that there are already 250 installed sites, it would be useful to develop a method to evaluate data without the need for a field test of every site.

It is important to underline that the ATK system is developed and used only for speed enforcement, and that the vehicle weight is a byproduct. There is no intention of using the system for weight enforcement. The piezo sensors are installed in the asphalt layer 5-10 cm below the surface. This is much deeper that for dedicated WIM systems.

2. WIM & ATK systems in Norway

Weigh in motion technology has been the subject of different research approaches within the NPRA throughout the last years. Different types of sensors have been tested in previous projects. Traditional weigh in motion units consist of a load sensor, installed in the road and a roadside data logger, which is processing the signals. The two types of load sensors used and tested in Norway are piezoelectric cables and lineas quartz sensors (Haugen, et al., 2016).

The dynamic load signals from piezoelectric cables can be affected by the asphalt temperature (Vaziri, et al., 2013). Hence, these WIM systems need a device for adjusting the registered signals related to the actual local temperature. Many commercial WIM systems based on piezo cables include a temperature sensor installed in the asphalt. The Norwegian ATK units do not have such temperature sensors, since the units are developed for speed enforcement. Neither does the software from the data logger adjust the weight signals with respect to the current temperature. This study developed a post processing temperature calibration method, using free weather data from the Norwegian meteorological institute.

Several research approaches evaluated the accuracy of different WIM systems in many countries throughout the last years (de Wet, 2010). The NPRA is using two piezoelectric based WIM systems and the lineas quartz sensors from the manufacturer Kistler. Previous research from Haugen et al. (2016) and Tello (2015) showed that all piezo-based systems are vulnerable to over- and underestimation of the actual static vehicle weight. A commercial piezo-based WIM system underestimated the static vehicle weight up to 25%. Additionally, a variation of the accuracy of the systems over certain periods was documented. Especially piezoelectric WIM systems varied significantly in their accuracy over a period of a few months (Haugen, et al., 2016). Calibration factors helped to improve the data quality of the WIM systems in these studies (Pedersen & Haugen, 2017). The detailed examinations of Haugen et al. (2016) and Tello (2015) indicated for all piezoelectric based WIM systems in Norway systematic errors.

The previously mentioned research approaches indicate that data from piezoelectric sensors is often lacking a desired level of accuracy. The fact that these commercial piezoelectric WIM systems were hardly able to provide accurate and reliable data over a longer period motivated the NPRA to investigate the possible use of weight data from ATK sensors for WIM purposes.

As mentioned, these ATK systems do also use piezoelectric cables, but are in general not optimized for weight data collection. The high amount of 250 available sites offers a good source of vehicle weight data across the entire country. Each ATK point could potentially provide the NPRA with WIM data at a negligible cost. This project has a high potential benefit, since the roadside infrastructure already exist.

3. Methodology

This study evaluates the quality of WIM data from ATK units in a two-step approach. First, the static weights from a close-by inspection site are compared to the dynamic weights measured with the ATK system. The ATK unit is categorized into an accuracy class, following the categorization from the COST 323 report (Jacob, et al., 2002). Second, a post processing data calibration method is developed in order to examine a possible increase in the accuracy of the data. This project does not look into why the accuracy is low in certain sites, the main focus is to identify which sites have accuracy good enough for statistical purposes.

3.1 Quality assessment

A common method to evaluate the quality and accuracy of WIM data are field tests. During these tests, static and dynamic vehicle weights are compared to each other. This test could either be done by checking the weight of trucks from the free flow traffic or by using pre-weighted vehicles. The tests performed in this project used trucks from the free flow traffic and indicate the performance of the examined ATK sites for the day of the particular test.

The collected static weights from local inspection sites can be assumed as very accurate and close to the actual weight of the vehicle. The weight sensors of these local inspection sites are calibrated frequently, since they are used for the enforcement of overloaded vehicles. The static axle weight of vehicles were registered and compared to the corresponding dynamic ATK weight during several field tests. These tests were performed in different parts of Norway at inspection sites, with nearby ATK sites. During a field test different types of heavy vehicles from the free flowing traffic were stopped. Static axle weight was measured and matched to the related weight from the ATK units near by. The detailed matching of the vehicles was done with the help of video recognition from both the static weight stations and the ATK unit.

The study evaluated the field tests with respect to the European WIM standard, defined and implemented by the COST 323 report (Jacob, et al., 2002). The COST 323 report defines several accuracy classes (AC) for weigh-in-motion data. Each AC is labelled with a letter from A to D, where A equals the best accuracy class and D the lowest. Each letter is followed by the tolerance of the relevant confidence interval in percent. Table 1 gives an overview of the accuracy classes and the given tolerances.

Table 1 - COST 323 accuracy classes (AC) and tolerances (T) in % (Jacob, et al., 2002)

AC	A	B+	C	D+	D	E+	E
T [%]	5	7	10	15	20	25	>30

The COST 323 report also defines a range of applications for each accuracy class (Jacob, et al., 2002). The highest classes (A and B+) can be used for the enforcement of legal weight limits. The accuracy classes B and C are sufficient to investigate the fatigue and wear of asphalt or for a pre-selection of potentially overloaded vehicles. The classes C to D can be used for utilizing weight data for statistical purposes in economical and technical studies (van Loo & Lees, 2015). Since the main focus of this study is the statistical evaluation of weight data, a high accuracy class, such as A or B+ is not necessarily needed for this field of application.

3.2 Calibration

For this project an additional quality indicator, which describes the weight data quality of an ATK site without performing a field test, is highly welcomed. A characteristic vehicle class (CVC) could fulfil that demand by delivering comparable weight data of a specific vehicle type. In most countries and road networks, a group of characteristic vehicles can be identified. A group of characteristic vehicles consists of similar vehicles with a low variation and a constant mean gross- or axle weight (van Loo & Lees, 2015). The chosen group of characteristical vehicles in this study are six axle semi-trailer vehicles. These vehicles are common in Norway and have a legal weight limit of 50 tons. Previous research, done by van Loo and Lees in 2015 on quality indicators for WIM systems showed, that especially the weight of the first axle of vehicles in this group is quite stable in a range between 6.5 and 7 tons. The first axle of a semi-trailer vehicle seems to have a lower variation in weight compared to the other axles, since it is less affected by the load on the trailer (Vaziri, et al., 2013). The calibration method in this study is based on the assumption of a relative stable interval for the weight of the first axle of a six-axle semi-trailer vehicle within a recommended range of 6.5 to 7 tons. Previous research by the NPRA tested and confirmed the applicability of these values on the Norwegian road network, with an average value of close to 7.0 tons.

These findings motivated us to test a calibration method for the ATK units, based on the weight of the first axle of six axle semi-trailer vehicles. The actual measured average weight for a first axle of a six axle semi-trailer vehicle could be used as a quality indicator and as a baseline for further calibration. In one of the performed field tests, the sensors are measuring an average weight for the reference axle of 5.47 tons (Wd) while we assume that this value should be 7.0 tons (Ws). For the further calibration method, assuming an ideal weight of this axle of 7.0 tons. Equitation (1) shows the developed calibration factor for the ATK unit, using the mean value of the first axle of a six-axle semi-trailer vehicle from a local ATK unit (Wd) and the ideal value of 7.0 tons (Ws).

$$C_{ATK} = 1 + \left(\frac{(W_s - W_d)}{W_s}\right) \qquad (1)$$

The developed calibration method was applied to the collected dynamic weight of numerous field tests, performed throughout spring 2017. Results of these calibration approaches are presented in the results section of this study.

The study indicated that the weight of the first axle within the CVC could be used as a data quality indicator for weight data from ATK systems. Numerous field tests confirmed that the weight of the first axle of the CVC should be within a range of 5.0 to 8.0 tons with a standard deviation of not more than 20%. Field tests showed that ATK stations with poor data quality also had low first axle weights with a high deviation. The introduced quality indicator is a good way to get a first impression of the data quality of an ATK station without performing a field test.

4. Results

The result section is divided into two parts. The first part contains the evaluation of field tests of different ATK stations all over Norway. Results adjusted with the presented calibration method is applied and the accuracy of the method is discussed. The second part presents post-calibrated ATK data sets used to evaluate the weight distribution of heavy vehicles on different road segments in Norway.

4.1 Field tests

Figure 2 gives an overview over four different field tests, all conducted in the spring 2017 (Auråen E18, Gjerdemyra E18, Teigkamptunnel E6, Otta E6). Weight data from 74 to 92 heavy vehicles was collected. The static weight was measured at a local inspection site and the corresponding dynamic weights were measured at a nearby ATK site.

The measured dynamic gross weight (GW) is plotted against the according static weight as red triangles in Figure 2. A linear regression line (LRL) is fitted to the data. The additional black y = x line would be the outcome of a 100% accurate WIM system, where every dynamic weight is equal to the static weight. All evaluated ATK points show similar characteristics. Most measured dynamic vehicle weights is underneath the black y=x line and is thus underestimating the static vehicle weight. The error between the static and the dynamic weight is increasing with increasing static weight. These results are in line with previously reported results on WIM systems and ATK units in Norway (Haugen, et al., 2016).

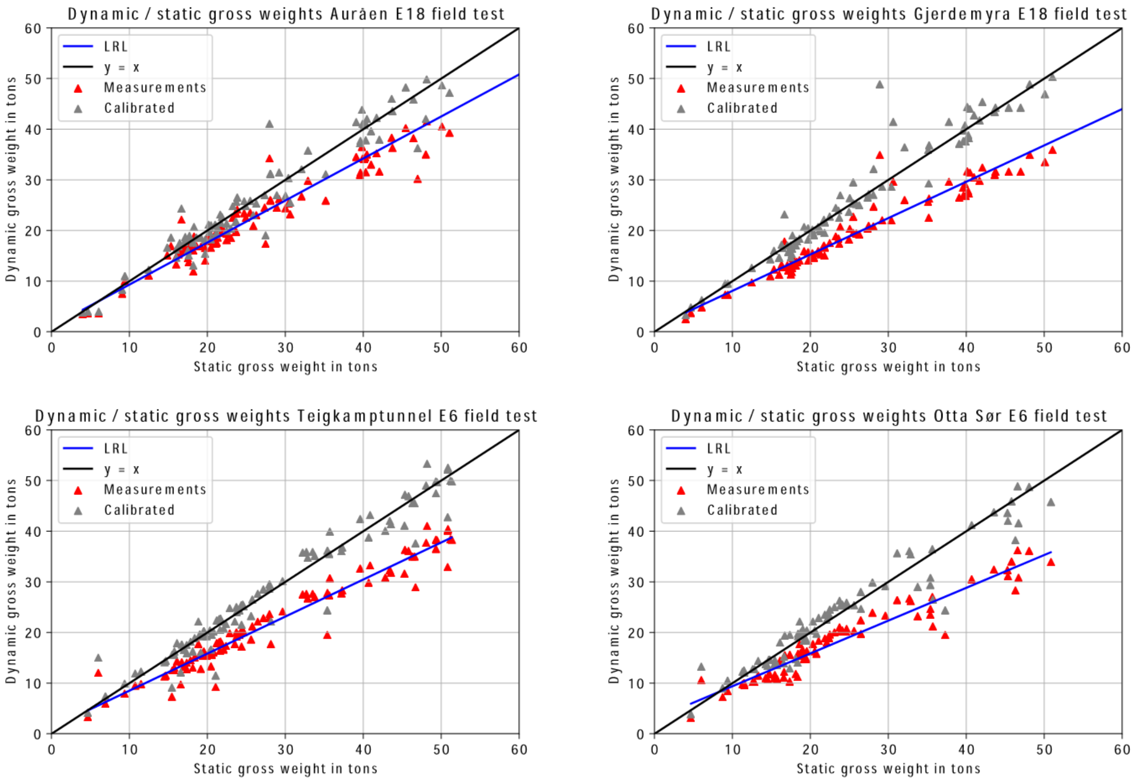

Figure 2 - Overview of the field test and calibration results

In order to improve the raw data quality, the previously presented calibration method (see Eq. 1) was applied to the raw ATK data sets. The calibrated data is shown in Figure 2 as grey triangles. In all four cases the data quality has improved after the calibration process. The calibrated measurements are of source closer to the actual measured static weights. To study the detailed effects of the calibration method, a closer assessment of the measurement errors is needed. Therefore, Table 2 gives a more detailed overview about the observed errors during the field test studies and after the calibration.

The errors in Table 2 shows the previously observed underestimation of the static vehicle weight by the ATK sensor. In addition, the results from Figure 2 seem to indicate visually that the calibration method is indeed improving the data quality. The calibrated measurements are located close to the x = y line which is representing an ideal WIM system. The mean errors before calibration are between -12,3% and -24,3%. Most of observed ATK data fulfils the accuracy requirements for the COST 323 accuracy class D, while one sensor is even within accuracy class D+. According to COST 323, data that fulfills the criteria of accuracy class D is good enough for being used for detailed statistical studies, which meets the requirements of this project.

Table 2 - Errors of the raw and calibrated data

Site	n	Mean error	SD error	Accuracy Class
Auråen	89	-12,3%	11,24%	D+
Auråen cal.	89	-0,59%	12,79%	D+
Gjerdemyra	85	-24,3%	8,29%	D
Gjerdemyra cal.	85	-0,82%	11,64%	D
Teigkamp.	92	-20,9%	15,12%	D
Teigkamp. cal.	92	0,1%	18,85%	D
Otta	74	-20,41%	14,46%	D
Otta cal.	74	0,87%	17,77%	D

All ATK sites have gradient less than 1%, and a cross fall of approximately 3%.

4.2 Long term data evaluation

The calibration method was afterwards applied to raw data, which was collected by three different ATK sites during a time period of 12 months. Two of these sites (Gjerdemyra & Otta) were already mentioned in previous tests within this study and in addition, a third one was added (Storsand).

Table 3 gives an overview of the amount of vehicle weight data collected for each of the ATK sites. The numbers are from one direction on a typical Norwegian 2-lane highway.

Table 3 – Number of registered vehicles at various ATK stations

Axle configuration	Gjerdemyra	Otta	Storsand
Number of vehicles	1 708 376	1 430 394	1 430 097
2 axle vehicles	1 472 052	1 216 334	1 310 661
6 axle vehicles	70 875	50 487	26 255
6 axle semi-trailers	49 793	33 604	17 297

Over a period of 12 months, between 1.7 and 1.4 million vehicles were detected and among them between 49 000 and 17 000 were six axle semi-trailer vehicles. Figure 3 shows the calibrated gross weight distribution for these vehicles.

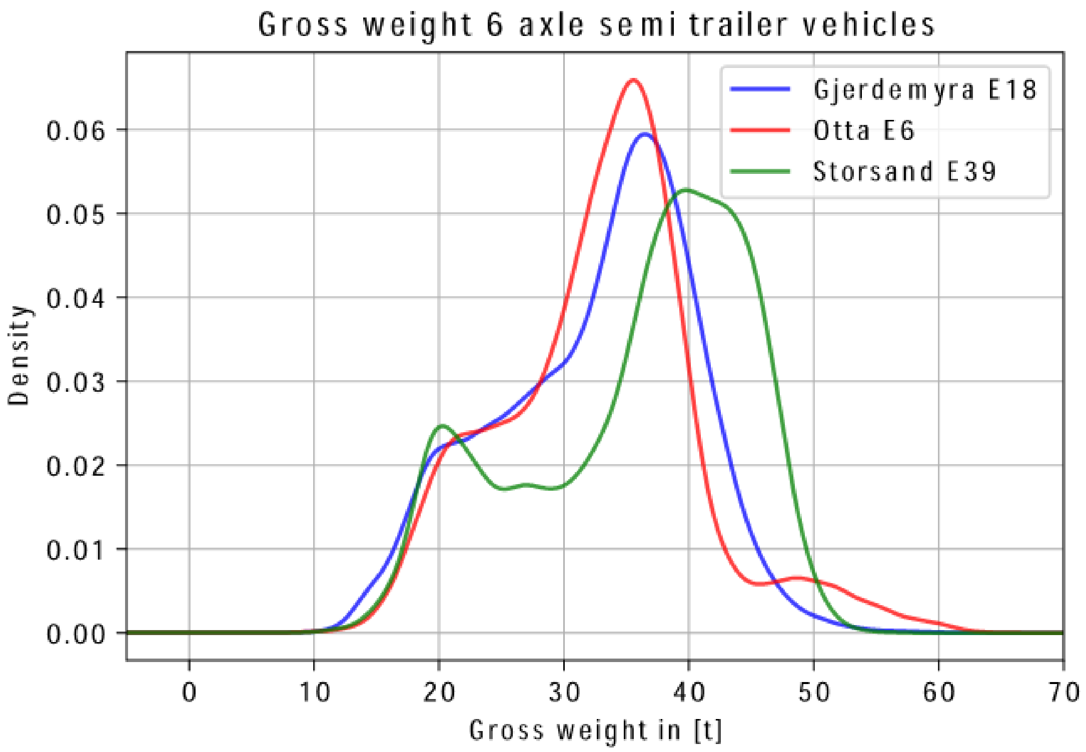

Figure 3 - Gross weight distribution

The three graphs are widely similar in their structure and in line with previous studied gross weight distribution of that vehicle category on the Norwegian road network. Nevertheless, the results show some interesting local characteristics of the plotted weight distributions. Storsand shows two distinct peaks in gross weight. The peak at 20 tons show unloaded vehicles. The amount of vehicles between 50 and 60 tons gross weight seems to be slightly higher in Otta, compared to the other two stations. The reason for that are timber trucks, which have special permissions in that region to extend their gross weight up to 60 tons, while 50 tons is the legal weight limit for that vehicle category on the Norwegian road network. That information is beneficial for pavement experts within the NPRA, since they are able to optimize the pavement structure based on this information.

5. Conclusion

The study evaluated the accuracy of weight data from piezoelectric based ATK sensors in Norway. Initial field tests gave an overview over the performance of the sensors and helped to establish a calibration and data quality evaluation method. The proposed calibration method was applied to improve ATK raw data sets.

This study indicate a systematic error between the dynamic weight from an ATK site and parallel measured static weight. These errors appeared in both traditional piezo-based WIM systems as well as at the piezo-based ATK sites. The dynamic weight data was found to be accurate enough for different applications, such as statistical analyses. Therefore, the data was analyzed with respect to the WIM accuracy standard COST 323.

The main goal of this study is not to enforce overloaded vehicles, but to gather statistical relevant information about the weight of vehicles traveling on different parts of the Norwegian road network. For this purpose the results are promising for further research approaches. Using the weight of the first axle of a six axle semi-trailer vehicle as a weight data quality indicator could be an interesting method for providing information about the performance of the sensors without implementing a field test at a local inspection station.

The study furthermore introduced the usage of this value as a reference for a raw data calibration. First tests with a developed calibration factor showed indeed an improvement of the accuracy of dynamic weights. Nevertheless, these are just the first experimental steps into the usage of weight data from ATK units. Ongoing studies are about to apply the developed methods to even more ATK sites across the country to gain further knowledge.

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ACCURACY REQUIREMENTS FOR WEIGH-IN-MOTION SYSTEMS FOR DIRECT ENFORCEMENT

  

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Abstract
In our work, we raise two problems that have not yet found a satisfactory solution: the use of an objective accuracy assessment method of WIM systems, and ensuring the high and stable accuracy of weighing results. In a light of near introduction of WIM's for direct enforcement, this seems to be a serious issue. In the paper, we present two criteria for assessing the accuracy of WIM systems for direct mass enforcement. First is reliability characteristic, the second one is tolerance intervals. Contrary to the widely used standard deviation, both methods take into account systematic (bias) component of the weighing results. We also discuss a method that allows continuous control of the accuracy of WIM systems during it operating in changing environmental conditions (uncertainty map). In this way, uncertainty can be assigned to each weighing result in an automatic manner.

Keywords: Weigh-in-Motion, accuracy assessment method.

Résumé
Dans notre travail, nous soulevons deux problèmes qui n'ont pas encore trouvé de solution satisfaisante: l'utilisation d'une méthode d'évaluation objective de la précision des systèmes de pesage en marche, et la garantie d'une précision élevée et stable des résultats de pesée. À la lumière de la quasi-introduction du WIM pour contrôle sanction automatisée, cela semble être un problème grave.
Dans ce document, nous présentons deux critères permettant d'évaluer la précision des systèmes WIM pour une application de contrôle sanction. La première concerne les caractéristiques de fiabilité, la seconde les intervalles de tolérance. Contrairement à la déviation standard largement utilisée, les deux méthodes prennent en compte la composante systématique (biais) des résultats de la pesée. Nous discutons également d'une méthode permettant un contrôle continu de la précision des systèmes WIM lors de leur fonctionnement dans des conditions environnementales changeantes (carte d'incertitude). De cette manière, une incertitude peut être affectée à chaque résultat de pesée de manière automatique.
Mots-clés: Pesage en marche, méthode d'évaluation de la précision.

1. Introduction

Extensive research has been conducted over last years into the application of WIM systems for direct mass enforcement purposes [1], [2], [3], [4], [5]. Examples are formal regulations introduced by the Czech Metrology Institute (CMI) [6] and by Hungarian Ministry of Transport. We may expect that in near future more countries will introduce WIM system into the mass enforcement practice.
Unfortunately, this process is still associated with some difficulties. Currently we may distinguished two partially resolved problems related to the introduction of WIM systems for direct mas enforcement [7]:

- the use of an objective accuracy assessment method,
- ensuring high and stable accuracy of weighing results in WIM systems.

The problem with the high and stable accuracy arises from the specific properties of WIM systems, where a complex of load sensor/pavement is a part of a measurement system. In result, the environmental factors and those directly associated with the weighed vehicle strongly influence the measurement results [8], [9], [10]. These factors affect all kinds of axle load sensors, regardless of the sensor technology. We divided them according to the source of their occurrence (vehicle or WIM system) or degree of influence (main or other). Figure 1 shows such a division.

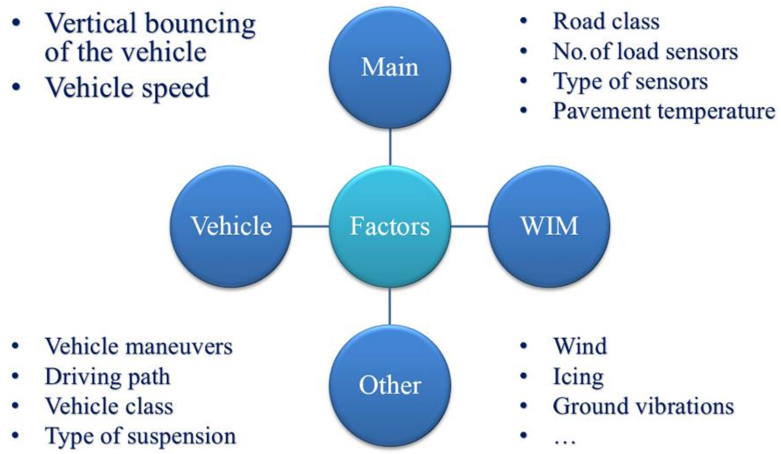

Figure 1 – Factors affecting the weighing accuracy with division according to the source of their occurrence (vehicle or WIM system) or degree of influence (main or other)

The importance of ensuring high accuracy of weighing results in WIM enforcement systems we will illustrate based on the following example. Figure 2 shows the distribution of GVW for tractors with trailers collected at exemplary WIM site. Let's assume the permissible GVW is 40 tons, so all vehicles with GVW above this value are considered to be overloaded and should be eliminated from the traffic. But due to the limited accuracy of weighing results, allowable values of GVW and axle loads must be increased by the amount of weighing error (assumed 10%). That procedure is required with a view to the necessary precaution, and allows avoiding a vehicle loaded within its ratings to be erroneously deemed overloaded. Consequently, a portion of vehicles that actually are overloaded will not be penalized (red shaded area in the Figure 2). In this case, just vehicles with GVW above 44 tons are considered to be overloaded (green shaded area at the Figure 2). There is also a reverse phenomenon. Due to the occurrence of weighing errors, some overloaded vehicles can be considered as normative.

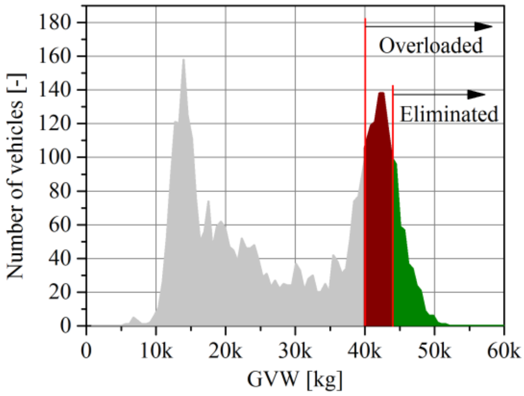

Figure 2 – Distribution of the GVW and the influence of the WIM system accuracy on the effectiveness on the elimination of overloaded vehicles

It follows from characteristic in Figure 2 that in order to ensure the effectiveness of a mass enforcement system, the weighing error should be as low as possible. In addition, the system requires frequent re-verifications due to daily and seasonal changes of climatic factors, which strongly influence this accuracy. This effect makes it necessary to extend additionally the area marked in red in Figure 1.

The second problem related to the use of WIM system for direct enforcement is reliable accuracy assessment method. Several such methods for WIM's have been proposed in the literature and put into practice [11], [12], [13], [14], [15], [16]. Some of the methods focus on the analysis of standard deviation of relative errors set and describes only the random component of the error, some of them take into account the systematic component, so called bias error. In case the system properties changes, for example due to temperature drift of the load sensor/pavement complex, a bias error appears in the weighing results. Thus, to assess correctly the accuracy of the system, a criterion should take into account a bias error.

In the paper we discuss two mentioned problems, which in our opinion, still have not been fully resolved: the use of correct method of assessing systems accuracy and ways to improve stability of the systems accuracy. It seems that the development of a joint approach at the international level in these areas would bring us closer to reliable implementation of WIM systems for direct enforcement.

2. Accuracy Criteria

In this chapter we present our approach to determining the accuracy criteria of WIM systems based on the population of weighing errors evaluated during system testing. The first method is related to the determination of WIM system reliability characteristic while the second one - to the determination of tolerance intervals for weighing errors. Both methods take into account bias error of the weighing results.

2.1 Reliability Characteristic

The reliability characteristic used for WIM systems accuracy assessment was developed by the authors and presented in details in [17]. The method uses several pre-weighed vehicles (with GVW selected in such a way as to cover uniformly the measurement range of tested system) repeatedly passing through the WIM system with different speeds. From the obtained measurement results a set of relative errors, computed according to the relation (1), is determined. No assumption regarding error distribution is needed.

$$\delta_i^{abs} = |\delta_i| = \left|\frac{w_i - w_i^{ref}}{w_i^{ref}}\right| \tag{1}$$

where:

w_i – a weighing result of the i-th pre-weighted vehicle obtained from the tested WIM system,

w_i^{ref} - a reference result of weighing the i-th vehicle pre-weighted on a static scale.

Our approach is based on the statistical analysis of the experimentally determined set of errors (1) using the characteristic (2) for this purpose.

$$\Phi(\delta^{abs}) = 1 - P(\delta^{abs}) \tag{2}$$

where:

$P(\delta^{abs})$ – a cumulative distribution function,

δ^{abs} – a random variable, which values constitute modules of the relative error values (1).

The characteristic (2) is called a system reliability characteristic and determines the probability of the occurrence of a weighing error with a value greater than δ^{abs}. Thus, on this characteristic we can also distinguish an error $\delta_{0.95}$ with a value corresponding to the probability of its occurrence P=0.05.

The reliability characteristic can be directly estimated on the basis of error values (1) obtained during WIM system testing and provides comprehensive information about the system accuracy. For example, in Figure 3 two characteristics are shown with the same value of $\delta_{95\%}$ = 0.06 (6%).

Distinguishing between these systems based solely on the standard deviation or 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.

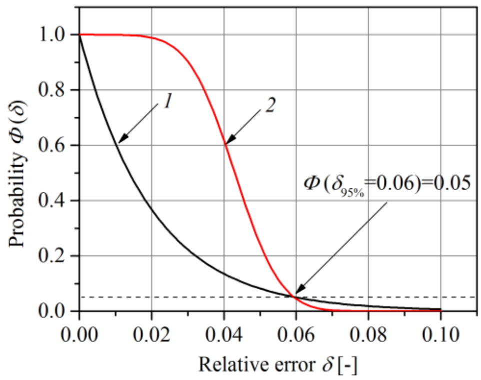

Figure 3 – Examples of reliability characteristics

2.2 Tolerance Interval

The task of WIM system accuracy assessment may be formulated as follows: *on the basis of the results gathered during the WIM system testing, the boundaries of the statistic interval (within which will be placed errors of a given part of the future weighing results, e.g. 0.95) should be determined.*

The solution for such a problem, for a random variable with a normal distribution, was developed by Wilks in 1941 [18] and Proschan in 1953 [19]. The interval, fulfilling such formulated expectations of the WIM system user, is called a tolerance interval and its boundaries are determined with the dependence (3) for the probability p=(1- α).

$$\delta^{\pm}_{(1-\alpha)} = \hat{\mu} \pm t^{(N-1)}_{(1-\alpha/2)}\sqrt{\frac{N+1}{N}}\,\hat{\sigma} \tag{3}$$

where:

$t^{(N-1)}_{(1-\alpha/2)}$ – Student's t distribution variable with $(\mathrm{N}-1)$ degrees of freedom, determined for the probability $(1-\alpha/2)$,

N - population size i.e. the number of measurement results (errors) obtained during the WIM system test,

$\hat{\mu} = \frac{1}{N}\sum_{i=1}^{N}\delta_i$ - estimate of the expected value,

$\hat{\sigma} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\delta_i-\hat{\mu})^2}$ - estimate of the standard deviation,

δ_i for $i = 1, 2, \ldots N$ - error values (1) gathered during the system testing.

The boundaries of the tolerance interval (3) are determined on the basis of a finite number of the observed elements of a general population. In consequence, the dependence (3) only enables these boundaries to be estimated (in a statistic sense). This means that, due to multiple repetitions of the whole procedure, a set of values of random variable boundaries (3) will be obtained. This variability causes that the probability p, that an element of the general population will fall into this interval, also varies. Consequently, it can happen that while looking for boundaries of the tolerance interval which corresponds to a probability $p = 0{,}95$, we will

determine the interval for $p = 0{,}91$ or $p = 0{,}98$. The size of sample population has a decisive effect on the uncertainty of the tolerance interval boundaries and thus on the variability of probability p.
In practice, the application of the tolerance interval for expressing the uncertainty of weighing results obtained from WIM system is complicated, since the bias error causes, that the tolerance interval is not symmetric with reference to zero. In such case it is defined by two numbers $\delta^{\pm}_{(1-\alpha)}$ differing in modulus. Thus, the uncertainty of weighing results obtained from WIM system can be assessed by taking into account the maximum values of modules of both boundaries of the tolerance interval, marked as:

$$\delta^{max}_{(1-\alpha)} = \max\left|\delta^{\pm}_{(1-\alpha)}\right| \tag{4}$$

2.3 Expanded Tolerance Interval

Underestimating the error value is unacceptable in WIM systems for direct enforcement. In the case of using these results for assessing administrative WIM systems, an over-optimistic estimation of their accuracy is especially dangerous. It could cause a standard vehicle to be considered as an overloaded one, thus assuming more cautious accuracy estimations is justified. Therefore, the accuracy of WIM system should be assessed based on the estimation of the maximum error value. For this purpose, an extended tolerance interval can be used (5).

$$\delta^{Ext\pm}_{(1-\alpha)} = \hat{\mu} \pm k\Delta\hat{\mu} \pm t^{(N-1)}_{(1-\alpha/2)}\sqrt{\frac{N+1}{N}}\,(\hat{\sigma} + k\Delta\hat{\sigma}) \tag{5}$$

where:

k – an arbitrarily assumed expansion coefficient,

$\Delta\hat{\mu} = \hat{\sigma}/\sqrt{N}$ – an uncertainty of the estimate of the expected value, determined on the basis of the test of the set size N ,

$\Delta\hat{\sigma} = \hat{\sigma}/\sqrt{2N}$ – an uncertainty of the estimate of the standard deviation, determined on the basis of the test of the sample set size N.

The assumed value of the expansion coefficient k depends on a cautious level of safety margin. As before, the uncertainty of weighing results can be assessed by taking into account the maximum value of modules of both boundaries of the extended tolerance interval (6), marked as:

$$\delta^{Ext\,max}_{(1-\alpha)} = \max\left|\delta^{Ext\pm}_{(1-\alpha)}\right| \tag{6}$$

3. Simulation test and results

To simplify the interpretation of the results, simulation tests were carried out for an error population (1) with a normal distribution. The most general case was considered, with a negative systematic error (bias) and a random variability of measurement results. Therefore, it was assumed that the expected value of error population is μ = -0.15 (bias error 15%), and the standard deviation is σ = 0.1 (random component 10%). This results in an asymmetric probability distribution with reference to zero. In addition, it was assumed that the size of error population is *N*=30, which is a typical value in the case of testing WIM system using pre-weighed vehicles. The value of expansion coefficient k was equal to 2. For the assumed error distribution, the true values of $\delta_{0.95}$ and boundaries of tolerance intervals are:

$$2\sigma = 0.2 \text{ (precisely } 1.96\sigma)$$

$$\delta_{0.95} = 0.31$$

$$\delta_{(1-\alpha)}^{max} = 0.35$$

$$\delta_{(1-\alpha)}^{Ext\,max} = 0.44$$

Figure 4 shows:

- a probability density function (pdf) of error population,
- a probability density function abs(pdf) of absolute value of error population (1),
- a reliability characteristic.

The true values of errors are marked with vertical bars.

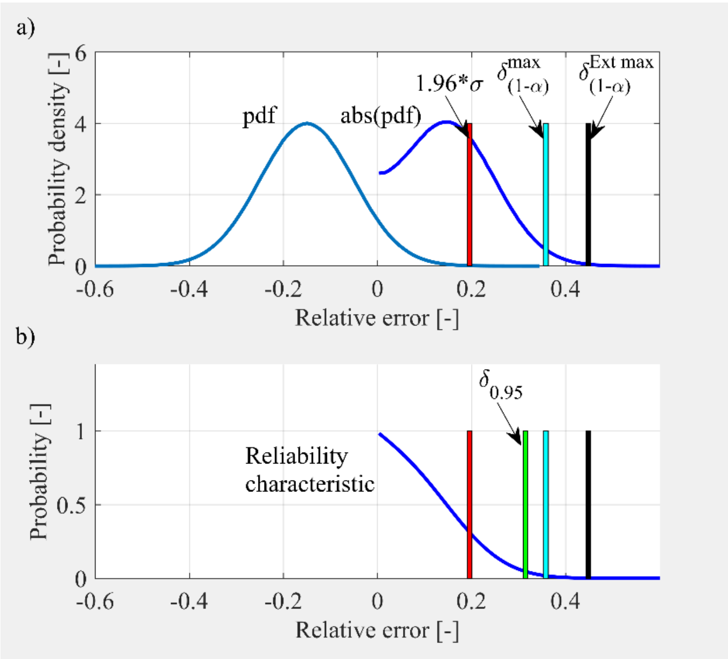

Figure 4 – a) Probability density functions pdf and abs(pdf) of error population, b) A reliability characteristic

For the considered, most general case with a negative bias error (μ = -0.15) and a small population of weighing errors (*N*=30) a few conclusions can be formulated based on Figure 4:

- The reliability characteristic and error $\delta_{0.95}$ are determined on the basis of module of error population (1). These estimators take into account both components of error: systematic (bias) and random. What is important, this will not cause underestimating of the WIM system uncertainty. Such an approach seems to be justified in WIM systems for direct enforcement of overloading. Standard deviation take into account only random component of the error population.
- Reliability characteristics provide comprehensive information on the system accuracy and determine the probability of the occurrence of a weighing error with a value greater than δ^{abs},
- Double standard deviation 1.96σ has the smallest value in relation to other measures of system error. For this reason, the use of 1.96σ to assess the accuracy of WIM systems for direct enforcement increases the probability of an erroneous interpretation of the weighing results.
- For a common size of error population N=30, the error $\delta_{0.95}$ has a higher value than 1.96σ. Thus $\delta_{0.95}$ is a more cautious estimate of the system accuracy.
- The tolerance interval (4) gives an even more cautious estimation of the system accuracy. Its value is greater than the error $\delta_{0.95}$.
- The expanded tolerance interval (6) is a measure of error with the highest value. This is due to the applied expansion coefficient k. Thus, this measure reduces the probability of an erroneous interpretation of weighing results of a vehicle.

The errors 1.96σ and $\delta_{0.95}$ do not depend directly on the population size N of WIM system errors but they depend on whether the error distribution is symmetrical with reference to zero. In turn, the sample size N affects the tolerance interval and the extended tolerance interval estimators. To illustrate this relationship, a simulation was carried out for various sizes N of population of weighing errors and for two cases of error distribution: a) not symmetrical μ = -0.15 (bias error 15%) and b) symmetrical μ = 0 (bias error 0%) with reference to zero. In order to reduce the random variability of results, for each N value the calculations were repeated 1000 times, and the results were averaged. Figure 5 shows values of estimator $\delta_{0.95}$ and estimators (4) and (6) as functions of a population size N of the measurement errors. The true values of 1.96σ and $\delta_{0.95}$ are marked with horizontal lines.

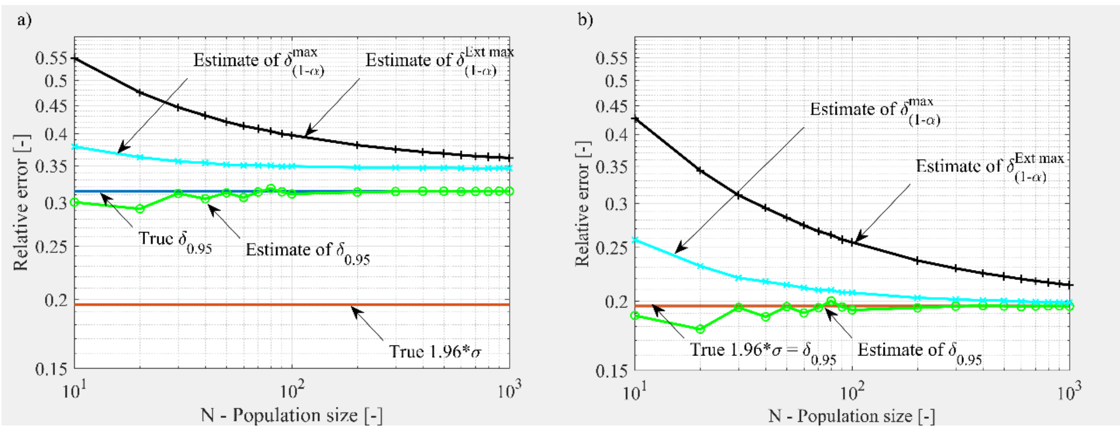

Figure 5 – Values of estimator $\delta_{0.95}$ and estimators (4) and (6) as functions of a population size N of the measurement errors for a) not symmetrical error distribution (μ = -0.15), b) symmetrical error distribution (μ = 0)

For the most general case with a negative systematic error μ = -0.15 (asymmetric distribution of errors with reference to zero) the following conclusions can be drawn from Figure 5a:

- Both criterions, $\delta_{0.95}$ and tolerance intervals, take into account bias error of the weighing results while standard deviation not.
- $\delta_{0.95}$ error has always a higher value than 1.96σ and gives a more cautious estimate of the system accuracy than double standard deviation no matter the value of the population size N.
- Estimates of tolerance and expanded tolerance intervals give even more cautious estimate of the system accuracy than $\delta_{0.95}$, especially for small N. This is a desired feature in WIM systems for direct enforcement.

For the case without systematic error μ = 0 (a symmetric distribution of errors with reference to zero) the following conclusions can be drawn from Figure 5b:

- This is a specific case where there is no bias error in WIM system and $\delta_{0.95} = 1.96\sigma$.
- Estimates of tolerance and expanded tolerance intervals asymptotically converge to the value of $\delta_{0.95}$.
- For N<100, which is a common situation for WIM systems testing, estimation of tolerance intervals gives more cautious estimate of the system accuracy than $\delta_{0.95}$ or 1.96σ. This is a desired feature in WIM systems for direct enforcement and prevents a normative vehicle from being considered as an overloaded one.

In both cases estimators $\delta_{(1-\alpha)}^{max}$ and $\delta_{(1-\alpha)}^{Ext\,max}$ give more cautious estimate of the system accuracy than $\delta_{0.95}$ or 1.96σ, no matter the value of the population size N. The relationship between measures of errors can be formulated as: $1.96\sigma \leq \delta_{0.95} < \delta_{(1-\alpha)}^{max} < \delta_{(1-\alpha)}^{Ext\,max}$. In a general case, when bias error exists in WIM system, double standard deviation should not be used as a measure of WIM system accuracy.

4. Stability of System Accuracy

Correct assessment of system accuracy is one issue but improving and stabilizing its accuracy is another challenge. It should be remembered that in case of WIM's the road surface is a part of the measuring system. The features of the road affects metrological parameters of the system [20], [10]. Among others, pavement temperature variations is most significant factor which cause changes of system accuracy. All WIM systems nevertheless of used axle load sensors, suffer from this effect. In Figure 6 we present measurement results from one of the Polish WIM site equipped with quartz sensors. It illustrates changes of relative error of weighing results over the time. For the accuracy assessment the reference vehicles method was used here [21]. At t=0 calibration of system was performed. But due to the temperature influence on the pavement and thus on the weighing results, 12 hours after calibration relative error was equal 8%. This phenomenon was repeated periodically every 24 hours according to the temperature changes of the pavement. In case of WIM's for direct enforcement such situation cannot take place.

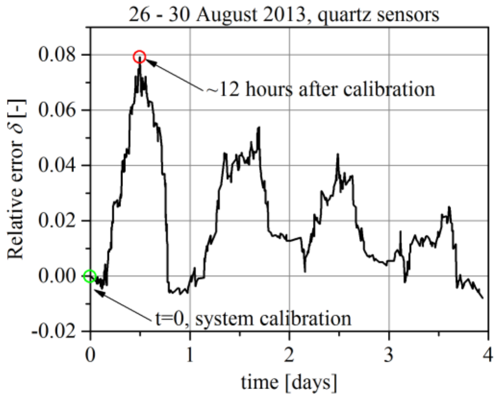

Figure 6 – Accuracy of WIM system equipped with quartz sensors

As we can see in Figure 6 random and systematic components are present in the relative error. Thus to correctly assess accuracy of the WIM system reliability characteristic or tolerance intervals method should be used.

The quantitative impact of some of the factors mentioned in the introduction on the accuracy of WIM systems was the goal of the authors' previous work. The subject of the research was, in particular, the impact of the surface temperature and the speed of the vehicle being weighed.

The paper [10] present a comparison of temperature sensitivity of load sensors made in three different technologies, i.e. polymer piezoelectric sensors manufactured by Measurement Specialties Inc., quartz produced by Kistler and bending plate produced by IRD (Figure 7). At each site, the data were collected for at least 6 months. For the accuracy assessment of each WIM system, we used the reference vehicles method [21]. To distinguish temperature effects from the influence of vehicle speed on the weighing error, temperature characteristics were determined for the range of vehicles' speeds of 70km/h–80km/h and speed characteristics were determined for the narrow pavement temperature range of 10°C–13°C. The investigated systems were calibrated at the temperature 15°C and for the vehicle speed of 70 km/h, which yields $\delta = 0$ for those values.

Although quartz and bending plate sensors are characterized by a low temperature sensitivity, the change of the surface temperature in the range from -10^{o}C to + 30^{o}C results in approx. 7% change in the weighing result.

The second factor influencing the WIM accuracy was vehicle speed. The tests were carried out in the range from 50km/h to 90km/h. For all sensors an effect of vehicle speed on the weighing result was found. In the case of quartz sensors, the change in the weighing result was approximately 4%. In the case of polymer sensors, this effect was stronger and amounted to around 10% (see Figure 7b).

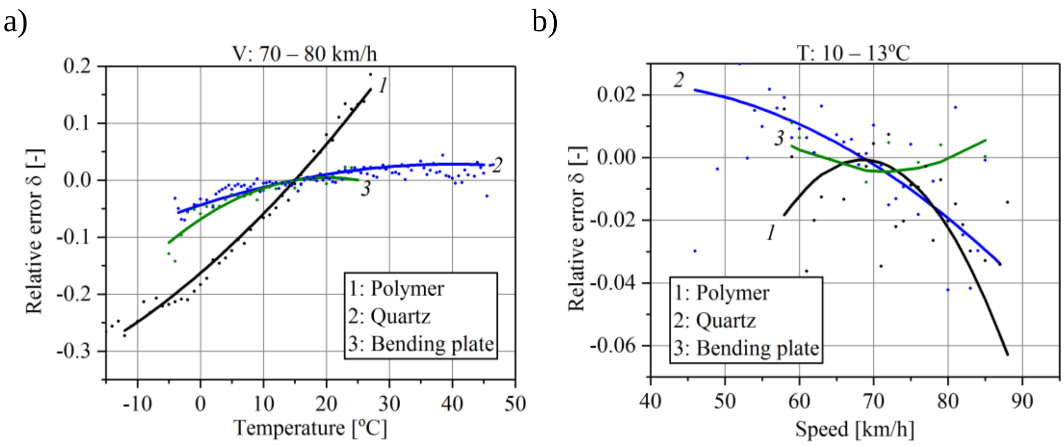

Figure 7 – (a) Temperature characteristics; (b) Speed characteristics of polymer, quartz and bending plate sensors installed in the pavement

5. Future Work

Because in weighing results two components, random and systematic exists, thus an important questions arises: how to assess the accuracy of the system as it changes? And how to deal with this phenomenon? What about influence of the other, random factors e.g. wind, heavy rain, snow? Their influence on WIM's systems has not been examined yet. To give answer on formulated questions and issues, new Weigh-in-Motion test site have been building by AGH-UST. The overview of the planned WIM test site is shown in Figure 8.

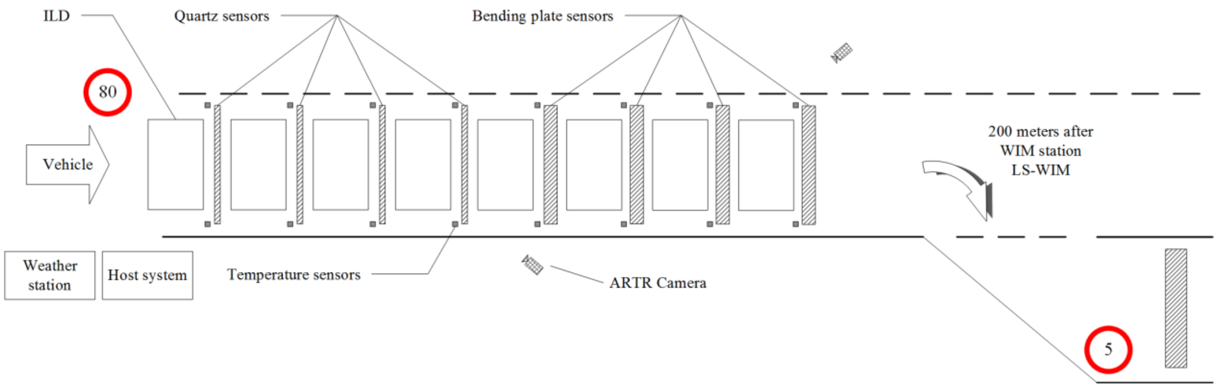

Figure 8 – Overview of the test site

The WIM site will be equipped with: 4 lines of quartz sensors, 4 lines of bending plate sensors, 16 pavement temperature sensors, "road sensors" – for detection of ice, snow, etc., weather station for meteorological quantities measurements, road surface vibration sensors. Site will be supplemented by Low-Speed WIM site for accurate weighing of the vehicle's axles. Currently (November 2018) all components have already been purchased by AGH-UST and are awaiting installation.

The test plan includes examining the effect of many factors on the weighing result:

- the temperature of the surface in which load sensors are installed,
- the speeds of the weighed vehicles and variability of their speeds during their passage through the WIM stations,
- wind speed and direction in respect of the direction of motion of the weighed vehicle,
- precipitation,
- surface icing,
- vertical oscillations of the vehicles' suspended mass and wheel hop,
- the characteristics of road surface where the load sensors are installed,
- changing surface parameters where WIM sites are installed,
- calibration frequency and method,
- the frequency of tests aimed at detecting system errors between subsequent calibrations,
- the implemented algorithm for the estimation of static axle loads and gross vehicle weights,
- fluctuations of the supply voltage,
- electromagnetic interference.

As it was mentioned before error or uncertainty in WIM systems changes over the time. 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 for authorities.
The solution which seems most useful for enforcement systems involves experimental determination of multidimensional space that describe the dependence of error and uncertainty of the weighing results on the influential factors (Figure 9). It is so called "safe subspace of interfering quantities" which defining the multidimensional subspace for interferences whose borders constitute their allowed intensity. If this intensity is included inside the borders, then the accuracy of weighing result is considered as acceptable. Such maps will enable controlling 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 administrative procedures.

The aforesaid uncertainty maps should be built separately for various classes of vehicles. The application of such uncertainty maps is possible only where WIM systems are equipped with measuring sensors for all significant influential factors.

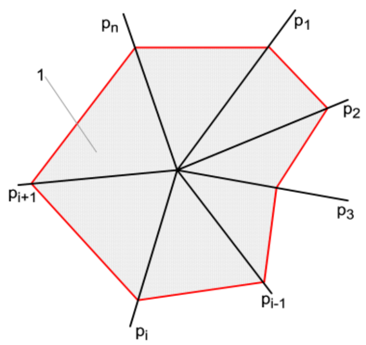

Figure 9 – Uncertainty map. p_i - i^{th}-influential parameter, 1 – multidimensional area in which the uncertainty of the weighing result is within the permissible limit

6. Conclusions

In many countries, activities are undertaken to introduce an automatic system of the mass control of vehicles. The implementation of this task requires solving both technical and formal problems. The paper presents authors' views on the criteria for assessing the accuracy of WIM systems used in direct mass enforcement systems. A method was also proposed that allows continuous control of the accuracy of WIM systems operating in changing operating conditions.

In the authors' opinion, the use of reliability characteristics or an extended tolerance interval to assess the accuracy of WIM systems is well-founded. This approach has some advantages over other solutions currently in use.

Also, the development of uncertainty map for the WIM system is possible under the current technical conditions. However, it means that the WIM system needs to be expanded significantly, by equipping it with additional sensors of all relevant factors interfering with the weighing process, but instead it enables continuous control of this uncertainty. In this way, uncertainty can be assigned to each weighing result in an automatic manner.

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ASSESSMENT OF HS-WIM SYSTEM AND CALIBRATION METHODS FOR DIRECT ENFORCEMENT APPLICATIONS

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Abstract
Currently, following successful experiences of other countries, regulatory agencies in Brazil have published norms in recent years to define guidelines and requirements for High Speed-Weigh-In-Motion (HS-WIM) systems. The requested standard consists of using HS-WIM for pre-selection of overweight vehicles, and for its subsequent weighing a static scale or Low Speed-WIM (LS-WIM). However, authorities are seeking the implementation of a direct enforcement model with these HS-WIM systems, a condition that still depends on more elaborate studies and tests, in addition to a set of standards that needs to be edited by the Brazilian National Institute of Metrology, Quality and Technology (INMETRO). Based on this scenario, we present this paper, which shows the results obtained from an evaluation of HS-WIM system, that includes tests of calibration methods and determination of the validity of measurement.

Keywords: HS-WIM, Direct Enforcement, Weigh-in-Motion, Overweight Trucks, Calibration Methods.

Résumé
À la suite des réussites récentes d’autres pays, les organismes de réglementation brésiliens ont publié des règlements ces dernières années afin de définir les directives et les exigences applicables aux systèmes de pesage en movement HS-WIM. La norme demandée consiste à utiliser la pesée HS-WIM pour la présélection de véhicules en surcharge, pour une pesée ultérieure dans une balance statique ou LS-WIM. Cependant, les autorités cherchent à mettre en œuvre le modèle de surveillance directe avec ces systèmes HS-WIM, cette condition dépend toujours d'études et de tests plus élaborés, en plus d'un ensemble de normes qui doivent être éditées par l'Institut Brésilien de Métrologie, Qualité et Technologie (INMETRO). Sur la base de ce scénario, nous présentons dans cet article les résultats d'une évaluation du système de pesage dynamique HS-WIM, comprenant des tests de méthodes d'étalonnage et la détermination de la validité de la mesure.

Mots-clefs: HS-WIM, surveillance directe, pesée en mouvement, camions surchargés, méthodes d'étalonnage.

1. Introduction.

In recent years, the Brazilian government has shown interest in the use of HS-WIM for weight enforcement in its road network. Regulating agencies, at the federal and state levels, have launched guidelines and regulations for implementation of these systems. Currently, enforcement for overweigh vehicles in Brazil follow a standard using a dedicated lane with Multi Sensor-WIM (MS-WIM) system, with a further weighing, using a LS-WIM system, Static precision bending plate or even portable scales. These new regulations seek to replace these older patterns with the pre-screening weighing at highway speeds, including subsystems for vehicular identification and classification. However, as pavement deterioration due to overweight trucks is a chronic problem in the country, the Brazilian authorities are interested in implementing a model of direct enforcement with HS-WIM.

Still, this model depends on more elaborate studies and tests so that INMETRO can publish a set of safe standards for these equipment. Despite the work presented by Doupal (2011) and Chou (2011), which provided technical foundation for direct enforcement experiences in the Czech Republic and Taiwan, there are still many barriers and concerns by INMETRO for this to become a reality in Brazil. To address these issues, the Federal University of Santa Catarina (UFSC) signed an agreement of technical cooperation with private companies and the federal government, through the National Department of Transportation Infrastructure (DNIT), to test technical solutions and evaluate the efficiency and accuracy of the WIM Systems.

2. Description of the test-site environment.

The test-site is located in the Municipality of Araranguá, State of Santa Catarina, Brazil, at a weigh station that belongs to DNIT, which contains a LS-WIM scale certified by INMETRO. At this same site, two segments of road were built for the installation of the HS-WIM, one out of concrete and another of asphalt, where both meet Class I - Excellent specifications of COST 323 (2002). These pavements were built to guarantee the implementation of HS-WIM for systems up to class A(5), which allows for the application of direct enforcement. The concrete segment is located at 1 km and the asphalt at 2 km before the weigh station.

For the tests described in this paper, two aligned lines of piezo-quartz sensors were installed on the asphalt segment of the road. An additional line of two piezo-polymer sensors were installed diagonally to the other sensors, for the determination of vehicle lateral position and detection of single and twin tires. A datalogger, a charge amplifier and an analog-to-digital converter were used to collect the data of all sensors.

In addition to these equipment, the system has inductive and magnetometers sensors for vehicular reidentification and determination of the magnetic signature. Finally, cameras with embedded license plate readers and real-time communication with the weigh station allows for the data to be continuously compared between the HS-WIM and LS-WIM. Figure 1 shows the installation diagram of the sensors.

The low speed scale used for collecting the reference values is located 2 km ahead of the location of the high speed sensors. This scale is operated by DNIT, and it was initially homologated and tested according to the standards of INMETRO on January 16^{th}, 2015. At that time, the performance achieved was the class 2 according to OIML R 134 (±1% error on initial verification and ±2% error for in-service). Since then, the scale must be recalibrated (in-service verification) once a year, and it must respect the following criteria:

- 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.

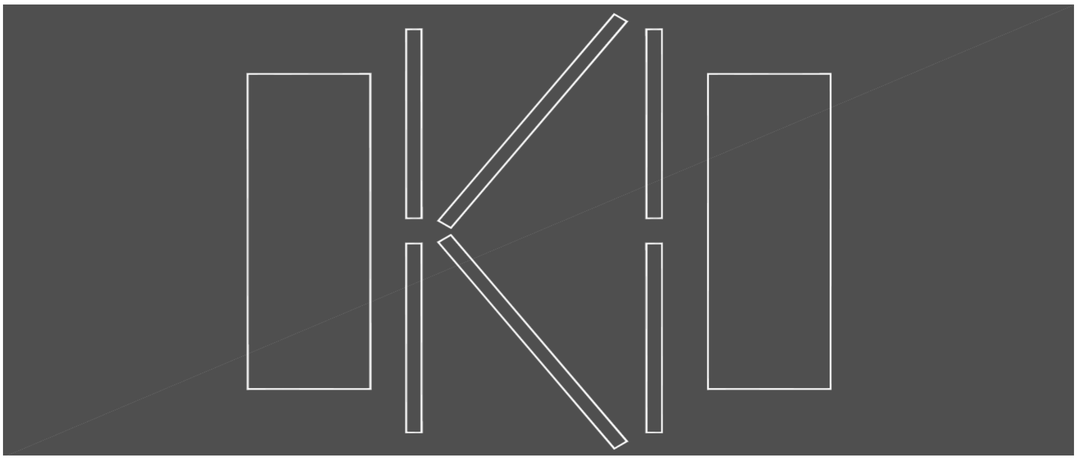


Figure 1 – Installation diagram.

3. Test procedures and configurations.

3.1 Pre-calibration and in service verifications.

The pre-calibration procedure adopted was with two different models of pre-weighed truck silhouettes, a single rigid truck with a single front axle and a rear tandem axle; and a semi-trailer tractor supporter by a single axle and a tandem, plus a trailer with triple tandem at the rear. Both correspond to categories 3C and 2S3 (see Table 6) of the Brazilian Vehicle Manufacturers Guide (QFV), respectively, representing two very common silhouettes and also used in the initial and in-service verification procedures for LS-WIM scales. Thirty runs were made with each vehicle at different speeds, small lateral positions variations and different loads according to the procedures described for (R1) - Limited Reproducibility Conditions, according to COST323 (2002).

After the procedure above, a test plan was developed to check the accuracy and to calibrate the system, this test consisted on collecting data from the normal traffic flow and comparing it with the data of the precision bending plate scale, using the vehicle re-identification feature. Those in service verifications were carried throughout several days, for periods not longer than four hours per day. This procedure was adopted to minimize the effects of temperature variation, which could add an error in the data analysis. Thus, all data collection, as well as the calibration procedures for the sensors were performed at the same time period every day, with the ground temperature being measured at the beginning and at end of each test, to be sure of its uniformity during the whole process. This way, the conditions considered for this test were (R2) – Full Reproducibility and (I) – Environmental Repeatability. The results obtained can be seen in Table 1.

After analyzing the results, we verified the occurrence of outliers, and also tolerance *[δ, -δ]* and confidence interval π above the expected ranges recommended for direct enforcement A (5).

Table 1 – Initial test results after first in service verification.

	N Samples	Mean	Std Dev	Π0	Class	δ	δmin	Π
Gross Weight	350	2,52%	4,49%	94,2%	C(15)	15%	10,1%	99,6%
Group of Axles	1090	6,13%	4,67%	94,8%	C(15)	18%	13,1%	99,3%

The table presents only the data for a group of axles due to the Brazilian legislation, which determines that weight enforcement can be done only for GVW and excess on a group of axles, as a result, the low speed scale system merge the measurements from single axles into a group of axles, following the instructions of the Brazilian Vehicle Manufacturers Guide (QFV) to perform this classification (steering axles, tandems, tridems, etc.).

3.2 Applications of filter techniques and validity of measurement.

Most of the data outside of the tolerance margin and outliers of the first analysis had standard inconsistencies on the output coming from other sensors. They were vehicles that were accelerating or deaccelerating between the piezo sensors, vehicles swapping lanes, among other maneuvers that affected the measurements. Therefore, as already pointed out by Doupal (2011) in his article “Base for Enforcement WIM Systems” when testing new HS-WIM systems, auxiliary features are necessary to reduce these errors.

Data from the piezo-polymer, quartz and inductive loops (magnetic profile) were used to detect all movements that affected the weight in motion, with the purpose of correcting and eliminating spurious measurements. Figure 2 shows a system screen indicating the magnetic profile feature used to eliminate the previously mentioned errors. Once the magnetic signature is characterized, any variation between the two inductive sensors associated with the piezo sensor data allows for a more accurate identification of the vehicle's trajectory and speed by the center of its metallic mass.

These variables define a measurement validity index, which allows you to define an algorithm with configurable limits to make the system more efficient, which would prevent unwarranted infractions. Table 2 shows the results after the implementation of this feature in the same sample of the previous test. It can be observed that the number of samples decreased, as a result of the elimination and correction of spurious measurements.

Table 2 – Tolerance and standard deviation measurement after validity of measurement tool.

	N Samples	Mean	Std Dev	Π0	Class	δ	δmin	Π
Gross Weight	295	1,58%	4,68%	94,1%	B(10)	10%	7,1%	94,4%
Group of Axles	950	2,98%	5,08%	94,7%	B(10)	13%	10,1%	97,1%

In order to confirm the efficiency of the algorithm, a new sample of vehicles were measured in the following days and the results can be observed in Table 3. After a second analysis of these new tests, it was seen again a small improvement in performance in relation to the tests without the validity of measurement feature, mainly in the elimination of spurious measurements.

However, with a more detailed analysis, the tolerance *[δ,-δ]* and confidence interval (π) are still slightly above the recommended levels for direct enforcement or pre-screening. When stratifying the data of this second sample, different rates of error can be verified for both, axle rank and vehicle profile, e.g. Table 4 and Table 5.

Table 3 – Tolerance and standard deviation measurement of new test sample after validity of measurement tool.

	N Samples	Mean	Std Dev	Π0	Class	δ	δmin	Π
Gross Weight	450	1,36%	4,49%	94,4%	B(10)	10%	7,1%	95,9%
Group of Axles	1400	2,20%	5,08%	94,9%	B(10)	13%	10,1%	97,9%

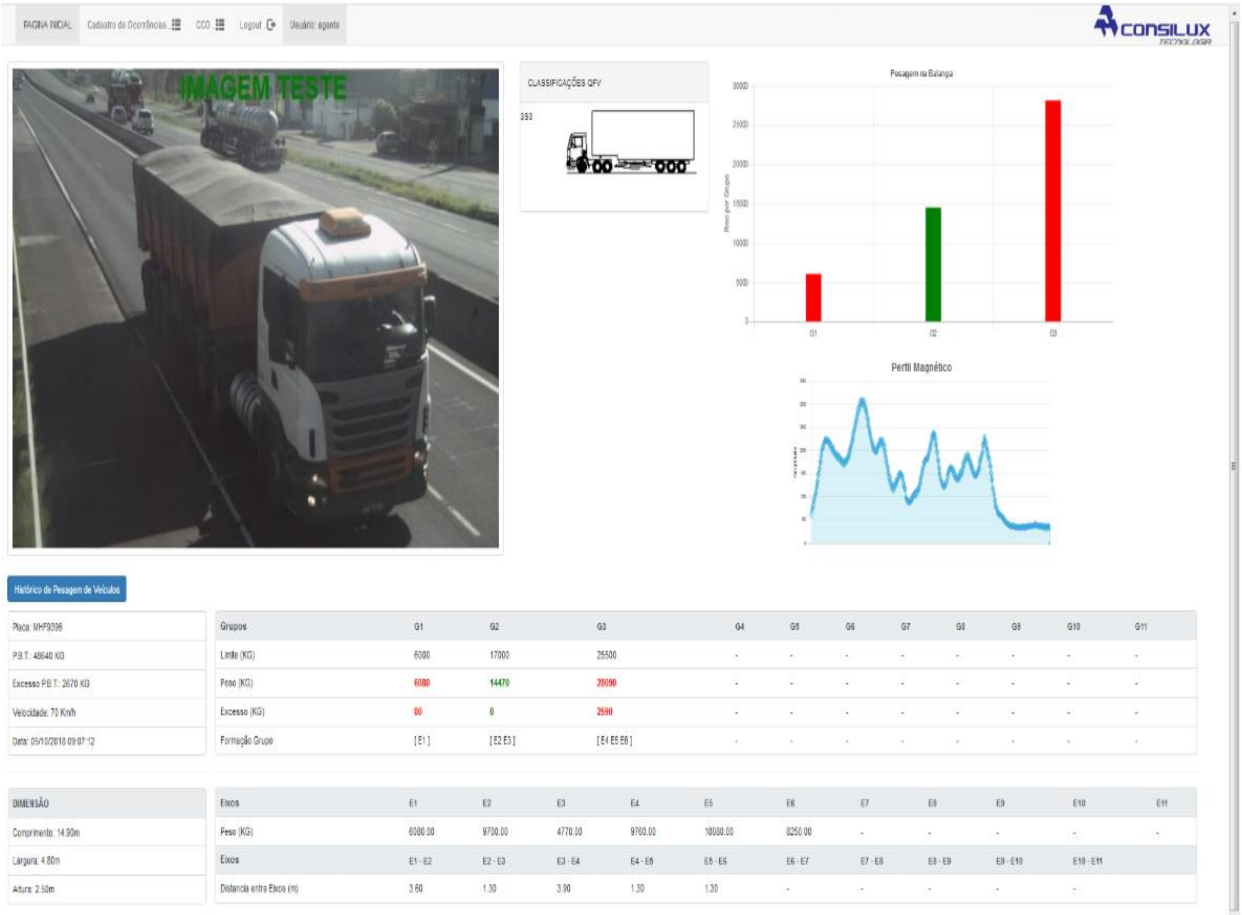


Figure 2 – System screenshot – sensors data.

As mentioned before, the low speed scale system classify the axles into a group according to the Brazilian Vehicle Manufacturers Guide (QFV), so it can also be observed in Table 4 the data collected considering this classification by axle rank (front axles, steering axles, tandems, tridems, etc.). The HS-WIM system installed in Araranguá has also this feature, and it turns possible the correlation of this data with the LS-WIM equipment.

Table 4 – Data by axle rank (weight of group of axles).

	N Samples	Mean	Std Dev	Π0	Class	δ	δmin	Π
Group 1	1400	-1,71%	3,39%	94,9%	B+(7)	10%	7,2%	99,1%
Group 2	1400	3,72%	4,45%	94,9%	B(10)	13%	10,1%	97,9%
Group 3	1092	2,29%	5,15%	94,8%	B(10)	13%	10,1%	97,6%
Group 4	462	5,09%	6,12%	94,4%	C(15)	18%	13,1%	97,8%
Group 5	175	3,90%	5,08%	93,6%	B(10)	13%	10,1%	94,8%

Table 5 - Data per truck silhouette (GVW).

	N Samples	Mean	Std Dev	Π0	Class	δ	δmin	Π
2C	19	3,85%	2,58%	87,1%	B(10)	10%	7,1%	96,3%
3C	85	1,56%	3,34%	92,6%	B(10)	10%	7,1%	98,8%
2S2	33	3,30%	1,45%	90,0%	B+(7)	7%	5,1%	98,2%
3S3	123	-3,20%	2,54%	93,1%	B(10)	10%	7,1%	99,3%
3S2	10	0,19%	1,46%	80,1%	A(5)	5%	0,1%	97,5%
2S3	62	2,24%	2,29%	91,9%	B+(7)	7%	5,1%	96,3%
3I3	53	1,27%	4,67%	91,5%	B(10)	10%	7,1%	92,3%
3M6	20	0,95%	1,89%	87,4%	A(5)	5%	0,1%	93,7%
3T4	17	1,13%	4,35%	86,3%	B(10)	10%	7,1%	89,8%
4CD	16	2,40%	3,35%	85,8%	B(10)	10%	7,1%	94,5%

The truck silhouettes presented in the Table 5 are described in the Table 6. Only truck silhouettes with more than nine valid samples were considered for this test.

3.3 Applications of automated self-calibration coefficients.

After this third analysis in the second sample test, as an opportunity for improvement, a resource for calculating an automated coefficient of calibration *C* were added to the HS-WIM system according to the axle rank and other for the truck silhouette. This self-calibration method is presented as a possible solution at the COST323 (2002) standard. For the implementation of this algorithm, it was made an analysis of the data pattern of each silhouette and axle rank collected and compared with the post-weighing at the LS-WIM. For this attempt, only classes with more than nine samples were considered in order to minimize undesired bias for lack of measurements.

Despite the large number of truck silhouettes that exists in the Brazilian market (over one hundred different classifications), it is verified by Table 5 that the normal traffic flow is restricted to only a few categories, which reduces the complexity and risk of the algorithm of correction of the self-calibration coefficient *C*. The images of the truck silhouettes described in Table 5 can be seen in Table 6. The twin tires are represented by black and white wheels, while single tires are represented by black wheels.

In this analysis, in spite of the small size of samples, it was possible to find some “characteristic values”, specially in the front axles of some silhouettes. With this “target value”, the software could estimate a different coefficient *C* for each class. It was also observed in this sample, that some vehicles silhouettes did not have its measurements centered into the confidence interval for some groups of axles, so for this cases, it was also added a feature to detect this deviation and calculate a factor to correct this issue. This was probably caused by the different influence of the pavement unevenness in each truck silhouettes.

After those analysis, the algorithm was implemented and tested in the second test sample to compare the performance. The results are seen on Table 7. In order to validate the software under normal traffic conditions, an additional third test sample was run to collect the data and check the performance with all features implemented (validity of measurement and self-calibration). The results can be observed in Table 8.

Although a slightly improvement in performance could be observed in those tests, the efficiency of this technique of a software for self-calibration must be tested under more rigid conditions, during a longer time and with bigger samples, since it can be affected for a lot of variables and introduce unwanted bias on the system. The time interval and size of samples used to calculate those different coefficient factors must be determined carefully with a higher amount of quality data.

Table 6 – Corrected data with the calibration coefficients – second sample.

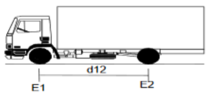
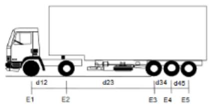
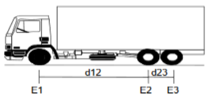
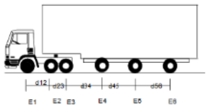
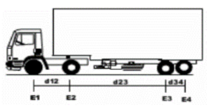
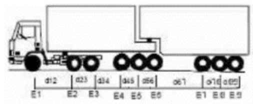
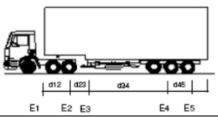
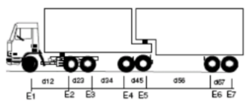
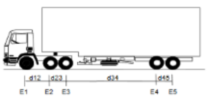
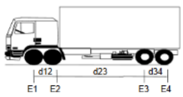
Silhouette	Abbreviation	Silhouette	Abbreviation
	2C		2S3
	3C		3I3
	2S2		3M6
	3S3		3T4
	3S2		4CD

Table 7 – Corrected data with the calibration coefficients – second sample.

	N Samples	Mean	Std Dev	Π0	Class	δ	δmin	Π
Gross Weight	450	1,17%	2,04%	94,4%	B+(7)	7%	5,1%	99,0%
Group of Axles	1400	2,37%	3,08%	94,9%	B+(7)	10%	7,2%	99,2%

Table 8 – Corrected data with the calibration coefficients – third sample.

	N Samples	Mean	Std Dev	Π0	Class	δ	δmin	Π
Gross Weight	330	1,20%	2,29%	94,1%	B+(7)	7%	5,1%	99,2%
Group of Axles	1040	2,20%	4,16%	94,8%	B+(7)	10%	7,2%	96,3%

4. Final considerations of the test and future projections.

There are still major challenges and definitions to be considered in deploying a direct enforcement project with HS-WIM, as observed from the tests performed. Even with the adoption of a 99% confidence interval (π), the nature of statistical weighing can cause unwarranted infractions, a fact that can discourage Brazilian authorities to move forward with a project.

Regarding the test site, there is still room for performance improvements. As also evaluated by Doupal (2011), temperature sensors and accelerometers offer a greater range of data for an active correction and assertiveness of the validity of measurement system.

INMETRO also has a key role in this process. The current regulation for enforcement with roadway scales only applies to LS-WIM and static equipment. It was based on the norm ROIML 134 (2006), with the addition of requirements for software security and vehicle classification. However, its mere adaptation to HS-WIM systems with the simple increase in tolerances does not seem prudent. As noted by the system evaluation performed, requirements for checking the validity of measurement and initial calibration require a thorough analysis by INMETRO when certifying the systems. The effort of only an initial verification with three tests vehicles may not represent that the system is with a satisfactory range of tolerance and confidence interval.

The exchange of information with international metrology institutes such as NMi Institute, whom is already more advanced in the definition of a standard and requirements for HS-WIM applications, together with data from the local test-site in Araranguá, could accelerate the implementation of direct enforcement by HS-WIM in Brazil.

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BRAZILIAN NATIONAL PROGRAM FOR VEHICLE OVERLOAD PREVENTION: PILOT APPLICATION





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Abstract
This paper describes the development and the pilot application of the Brazilian National Program for Vehicle Overload Prevention. This prevention program was created by the Brazilian National Department of Transportation Infrastructure (DNIT) in collaboration with the Transportation and Logistics Laboratory at the Federal University of Santa Catarina (LabTrans/UFSC) with the objective of establishing an alternative mean for vehicle overload control in Brazilian highways, thus complementing the traditional procedures for enforcement of road vehicles regulations. The concept of the program is based on the processing of Weigh-in-Motion (WIM) data in integration with national databases. The results of the pilot application have shown potential for a full program to be implemented with the support of the national WIM network. Accuracy verifications and quality checks were performed over the WIM data in order to ensure its reliability.

Keywords: Brazil, Prevention, National Program, Enforcement, Weigh-in-Motion, WIM.

Resumo
Este artigo descreve o desenvolvimento e a aplicação-piloto do Programa Brasileiro de Prevenção à Prática de Sobrepeso, criado pelo Departamento Nacional de Infraestrutura de Transportes (DNIT) em colaboração com o Laboratório de Transportes e Logística da Universidade Federal de Santa Catarina (LabTrans/UFSC). O trabalho tem como o objetivo prover uma alternativa para o controle do excesso de peso em veículos rodoviários, através de métodos complementares aos tradicionais processos de fiscalização. O conceito do programa baseia-se no processamento de dados pesagem em movimento (WIM) em integração com bancos de dados nacionais. Os resultados da aplicação-piloto demonstram potencial para que um programa completo seja implementado, com apoio da rede de sistemas WIM nacional. Por fim, verificações de desempenho e processos de controle de qualidade foram realizados sobre os dados de WIM a fim de garantir a sua confiabilidade.

Palavras-chave: Brasil, Prevenção, Programa Nacional, Fiscalização, Weigh-in-Motion, WIM.

1. Introduction:

The increase in the number of heavy vehicles and the surge of new traffic routes tend to contribute to the loss of effectiveness of traditional road inspection processes, especially when the law enforcement tools available are not flexible enough to keep up with these changes. In Brazil, the economic growth of the last two decades and the high dependence of roads for the transportation of commodities stand out as aggravating factors to this problem. In this context, the concept of the National Program for Vehicle Overload Prevention was developed based on the definition of strategies that go beyond roadside inspections and shows potential to contribute to the reduction of overloading vehicles traveling on Brazilian roads.

The pilot application described in this paper was carried out with three months of data from a high-speed WIM site installed on the right lane of the road BR-101 Southbound. This road stands as one of the main traffic corridors connecting the states of southern Brazil. The WIM site used for the pilot is made of two lines of piezoquartz sensors, integrated with a License Plate Recognition (LPR) camera. The system covers one lane, where 211,030 heavy vehicles were registered during the months of June, July and August, 2016. Thus, the pilot application of the Program was performed through four distinct stages:

- Investigation of overloading.
- Transport company profiling.
- Analysis of results.
- Definition of guidelines for prevention actions.

The first stage of the pilot application focuses on understanding the local overloading practices with the help of three consecutive months of high-speed WIM data. Through an established method for data processing, this part of the project provides hypothesis about how and when the overloading practices occur at the site under investigation. For this purpose, aspects related to the type and frequency of the overloading detected by the WIM system are assessed.

The second stage of the pilot application looks to identify and classify carriers with the most frequent and severe records of possible overload violations detected by the WIM system. From the processing of the WIM data, the correlation of overloading records with the respective transport companies allows for better targeting when designing the guidelines for prevention actions. For this pilot application, the identification and profiling of transport companies were limited to vehicles with Special Traffic Permits, whose database is managed by DNIT. Even though it was performed on limited scale, this stage of the pilot application showed promising results, where a large portion of the violations were concentrated among few transport companies.

On a third stage, the analysis of results takes places as a consequence of the previous stages. In this activity, the obtained results are analyzed and interpreted by enforcement officers and specialists, who interpret the data and draw hypotheses about the profile of the overloading practices in the studied area. Whenever possible, the hypotheses are tested, and the results of this analysis form the basis for defining the actions to prevent vehicle overloading.

The last stage of the pilot application consists of the definition of guidelines for preventive actions with potential to reduce the overloading levels of the site under investigation. In this activity, the conclusions drawn from the analysis of results stage support the design of guidelines for prevention actions specially focused on the characteristics of the local overloading and directed to the actors who may practice it more frequently and severely.

2. Investigation of overloading

The investigation of overloading is a stage in the project where a basic method of WIM data analysis is performed in order to support the definition of guidelines for prevention actions. For this purpose, three months of WIM data from the road BR-101 Southbound were collected and processed with the objective of providing general information about the type and frequency of overloading vehicles travelling through that site.

In order to evaluate "how" and "when" the overloading occurred more frequently and severely in the road segment under investigation, the following aspects about the practice of overloading were analyzed:

- Types of overload violations.
- Vehicle classes.
- Days of the week.
- Hours of the day.

According to Brazilian regulations, the Gross Vehicle Weight (GVW) limits are different for each vehicle class, which is defined based on the axle distances, axle types and vehicle length. The axle load limits, however, vary according to specific axle types (DNIT, 2012). It should be noted that all overloading records and their respective analyses in this study consider the applicable tolerances for each type of violation. Thus, according to Brazilian regulations, tolerances of 5% over the limits of GVW are allowed; and 10% over the axle and axle group limits (CONTRAN, 2015).

2.1 Types of overload violations

In Brazil, a vehicle overload violation may be framed as one of three distinct types (DENATRAN, 2016):

- Type 1 - GVW overload only.
- Type 2 - Axle overload only.
- Type 3 - GVW and axle overloads, simultaneously.

During the months of June, July and August, 2016, a total of 211,030 heavy vehicles were registered by the WIM site. Out of these 211,030 records, 33,067 (15.67%) presented some kind of potential overload. The graph on Figure 1 shows the percentages of overloading vehicles divided among the three different types of overload violations:

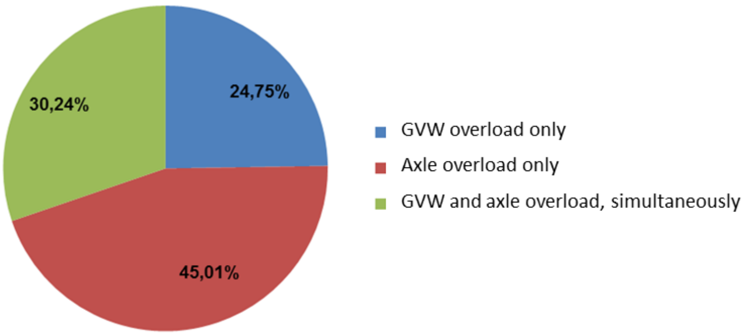

Figure 1 – Overloading vehicles by type of violation

2.2 Vehicle classes

In order to support of the investigation of the overloading practiced at the monitored site, the distribution of overloading records among the different vehicle classes was assessed, considering DNIT's vehicle class scheme (DNIT, 2012). Table 1 shows the top five vehicle classes with the highest overload frequencies during the three-month period when the study was conducted. The table also shows the percentages of overloaded vehicles and the most frequent overload violation of each vehicle class listed.

Table 1 – Top five most overloaded vehicle classes

Vehicle class	Number of vehicles	Number of overloaded vehicles	Percentage overloaded	Most frequent overload violation
3S3	33425	8730	26,12%	GVW only (57,17%)
3C	39570	7238	18,29%	GVW and axle (44,88%)
3I3	10328	3671	35,54%	Axle only (51,13%)
2S3	20902	2559	12,24%	Axle only (78,67%)
4CD	7268	2282	31,40%	GVW and axle (63,67%)

The silhouettes of each vehicle class listed on Table 1 are illustrated on Figure 2, along with their respective load limits.

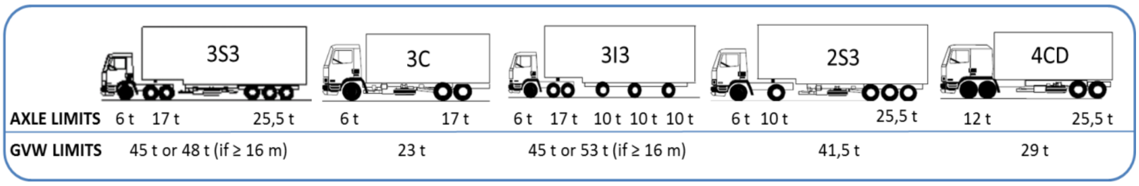

Figure 2 – Top five most overloaded vehicle silhouettes and its load limits

2.3 Days of the week

The graph on Figure 2 depicts the distribution of the number of vehicles and the records of overloaded vehicles grouped according to the days of the week, during the three months of monitoring.

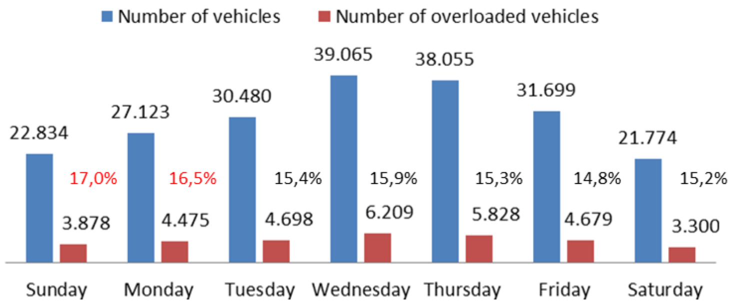

Figure 3 – Analysis of overload records by days of the week

Higher volumes of overloading were found on Wednesday and Thursday, which coincide with the days of highest truck traffic. When looking at the percentages, the highest rates of overloading were seen on Sunday and Monday.

2.4 Hours of the day

Based on the assumption that overloading records may be seen more frequently at certain times of the day, a survey over this type information was performed in order to help understanding the factors of influence over the local overloading practices. The graph on Figure 3 shows the frequencies of heavy vehicles and overloading records grouped in hour intervals, considering the three months of WIM data collection.

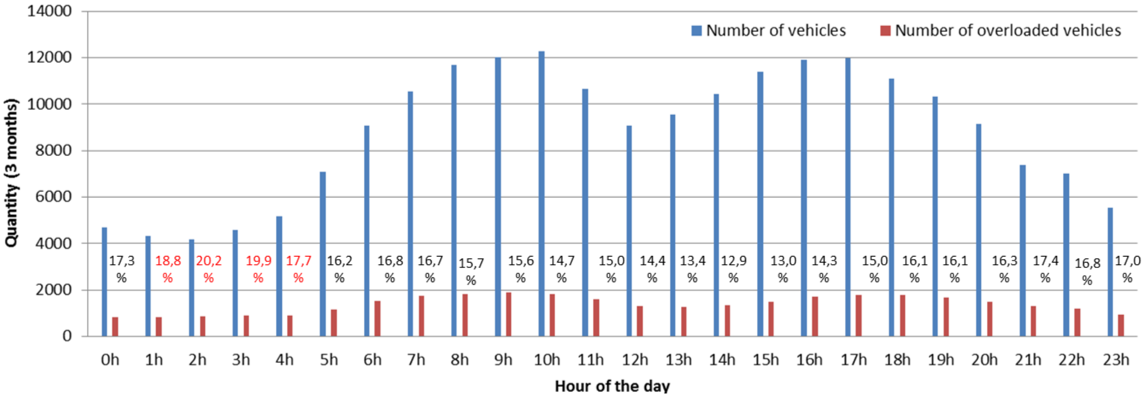

Figure 4 – Analysis of overload records by hour intervals

The analysis shows higher volumes of overloading between 8:00 e 11:00, which coincide with the hours of highest truck traffic. When looking at the percentages, the highest rates of overloading were seen in the period between 1:00 and 4:00.

3. Transport Company Profiling

The concept of transport company profiling has been used in countries such as The Netherlands and France, where companies with frequent presumed infringements are often targeted for warnings and in company checks (Jacob and Cottineau, 2016). In this pilot application, company profiling was performed on a limited basis, only for vehicles with the need for special transit authorizations, which are required for vehicles longer than 19.80 meters. This restriction on the scope of the transport company activity was due to the necessity of having a readily available transport company database in order to correlate with the overloading records. However, a cooperation agreement between DNIT and the National Land Transportation Agency (ANTT) may allow for full scale Company Profiling based on the National Register of Road Carriers, also known as the RNTRC (ANTT, 2018).

In the Company Profiling activity, the processing of the WIM data resulted in a list with the top ten carriers with the highest number of potential overload records among vehicles with Special Transit Authorizations. This list is shown on Table 2, where fictitious names were used in order to preserve the identity of the carriers.

Table 2 – Top 10 transport companies in overload frequency

Transport company	Overloaded vehicles
Padilha Ltda	110
Macedo Logística	81
Silva Transportes	28
LPG Locação	17
Marciel Transportes	15
Santos e Cia Ltda.	15
Expresso Sudeste	14
PJ Transportes	13
Transportes América	12
Castanhal Transportes	12

The results found in the company profiling stage of this pilot was sufficient as a proof of concept. In the monitored period, a total of 671 overloading vehicle records could have their license plate number associated with a transport company. Out of this number, 317 (47,24%) overloading records were concentrated among the companies listed on Table 2. Also, 191 (28,46%) of the possible violations accumulated over only two carriers.

4. Analysis of results

In this pilot application, the process involving the analysis of results occurred after the stages of overload investigation and company profiling. Based on the results from these previous activities, a technical team composed of specialists and enforcement officers from DNIT worked on the interpretation of certain trends observed through the WIM data collected. The officers' field experience enabled the formulation of hypotheses about the phenomena observed in the data, giving clues for its investigation in greater detail. Thus, this process of analysis and interpretation enabled the final formulation of guidelines for prevention actions.

In the analysis of results activity, the following phenomena were observed and studied in greater detail based on enforcement officers' input:

- Predominance of axle overloads over other types of violations.
- High frequencies of overloading on certain hours of the day and days of the week.
- High frequencies of overloading over certain vehicle classes.
- High frequencies overloading over certain transport companies.

4.1 Predominance of axle overloads

In the analysis performed, it was found that 14,883 (45.01%) of the overloading vehicle records referred to axles only, without any excess on GVW. Out of this total, only 2,474 (16.62%) were overloaded by more than 10% of the legal limits. Thus, it was found that much of the overloading on the road could be avoided by properly allocating the loads over the road vehicles. Therefore, it was concluded that the overloading levels could be reduced by means of actions aiming to promote the adequate distribution of vehicle loads at the origin of transportation.

4.2 High frequencies of overloading on certain hours and days

The collected WIM data indicated that the traffic of heavy vehicles and the volume of overload records were higher in the periods from 7:00 to 11:00 and 14:00 to 19:00. According to the experience of the local enforcement officers involved in the study, this phenomenon is related to the high volume of local freight carried out in the region, such as sand transport, where the trips are made in a short distance and the cargo is consolidated in larger vehicles in neighboring cities.

The percentages of potentially overloaded vehicles in relation to the total number of heavy vehicles travelling in each day of the week were greater on Sundays and of Mondays, when 16,98% and 16.50% of the heavy vehicles were overloaded, respectively. In the same context, when looking at hours of a day, it was found that the percentages of overloading were greater between midnight and 4:00.

Considering the results from the WIM data, it was hypothesized that some of the overloading trends may be associated with one or more specific industries that make up the fleet of heavy vehicles in the region where the data was collected. The days and times with the highest levels of overloading coincide with the periods in which the transportation of the brick industry is predominantly performed over the monitored site. According to the input from the enforcement officers, these transports tend to happen in the late night between Sunday and Monday, towards the metropolitan region of Porto Alegre and other cities in the south of Brazil, arriving at their destination before Monday's business hours.

4.3 High frequencies of overloading over certain vehicle classes

Two out of the five classes of heavy vehicles with the highest frequencies of overloading records detected by the WIM system presented particular phenomena that were investigated in greater detail.

4.3.1 *Vehicle class 3C*

Vehicle class 3C presented the second largest amount of overloading records among all heavy vehicle classes. Out of the 7,238 3C vehicles detected with some type of potential overload, 3,010 vehicles records referred to axle overloads, without exceeding the GVW limits. When analyzing this specific subgroup of vehicle records, it was found that out of the 3,010 vehicles with only axle overloads, 2,627 (87,24%) referred to overloads in the first axle.

Considering this concentration of overloads, hypotheses were drawn up and recorded based on the experience of the enforcement officers who operate at the site where the data was collected. According to the officers, 3C vehicles tend to present excess in their first axles. One of the reasons for this is the frequent lowering of the vehicle suspension, which causes a seesaw effect and increases the load on the front axle. Another potentially relevant factor relates to the position of the engine of some models of rigid trucks, which are manufactured over the front axle, facilitating its overload.

4.3.2 *Vehicle class 2S3*

The detailed analysis of class 2S3 axle overload records indicated that out of the 2,169 records, 1,858 (85,66%) referred to overloads in the second axle. Based on this observation, hypotheses were drawn aiming to explain this phenomenon, thus helping in the definition of guidelines for prevention actions in the region where the data was collected.

Based on the experience of the enforcement officers involved in the project, 2S3 vehicles are frequently overloaded in its second axle, which is vehicle's driven axle. In such cases, according to the officers, it is common for drivers to claim that it is necessary to place a certain load over the driven axle so that the wheel has the friction required for the vehicle to be driven.

4.4 High frequencies overloading over certain transport companies

Despite being performed on a limited basis, the results of the company profiling activity contributed to the hypothesis that the overloading practices tends to be concentrated among a small number of carriers. According to WIM data collected at the monitored site, two carriers were responsible for 28.46% of the overloading records.

In order to develop guidelines for overload prevention actions based on company profiling, the overload records by the top two most overloaded companies were studied in greater detail. During the monitored period, both "Padilha Ltda" and "Mecedo Logistica" had over 90% of "axle only" type of overload. Of this total, over 90% of both companies' overloads were below 10% of the legal limits, considering the current legal tolerances. This type of violation can generally be avoided by distributing and properly storing the load on the vehicle.

5. Definition of guidelines for prevention actions

The definition of guidelines for prevention actions aims to identify possible interventions that may reduce the overloading rates observed in the place where the WIM data was collected. In the context of this pilot application, the identification of potential prevention actions was the last stage of the project, when the conclusions from the analysis of results were drawn, allowing for the projection of actions specifically designed for the characteristics of the region where it will be applied.

The designed guidelines for prevention actions are summarized as follows:

- **Education sessions at inspection sites:** From 7:00 to 11:00 and from 2:00 to 6:00, when the absolute overloading frequencies are higher due to the higher density of heavy vehicles, this type of operation can be adopted along with the inspection processes.
- **Identification of commodity consolidation sites (e.g. sand):** The identification of these sites can enable better targeting of preventive actions to be carried out, considering that overloading was more significant at the times when this type of transport is predominant (business hours).
- **Inspection and education sessions in the early hours of Sunday to Monday:** The period between midnight and 4:00h on Monday shows a higher probability of random selection of overloads over 10% of the legal limit. In this type of prevention action, drivers can be educated about the risks related to overloading and the losses linked to the possible need for transshipment of the cargo.
- **Visits to companies with the highest overloading frequencies:** In the company profiling activity, the results show that almost half of the possible overloading records were concentrated in ten transport companies. Yet, roughly 30% of the overload records was concentrated in two companies. Thus, visits aimed at preventing overloading can occur in a number from 2 to 10 companies, depending on the availability of resources for this type of activity.
- **Visits to the brick industry:** The data collected in the pilot application and the experience of local officers point to a possible relationship between the high percentage of overloads recorded in the late hours between Sunday and Monday with the industries of construction materials located at nearby towns. This hypothesis may be tested through punctual inspection at the times when these transports tend to occur.
- **Education sessions about proper vehicle loading techniques**: In this pilot application, it was observed that 45.01% of the overloaded vehicles had "axle only" type of overload, with no overload in GVW. Of this share, 83.38% were registered with an excess of less than 10% above the legal limits plus tolerances. Thus, educating drivers and carriers about proper distribution of loads on road vehicles may help reducing a large part of the overloading on the road.

6. WIM performance assessment and data quality management

In order to verify the quality of the analyses carried out with WIM data, quality checks were performed, including on-site verifications on the WIM system and the use of a data quality management system for a second check of the consistency of the collected data. In this context, the results obtained for each of the three months of data collected, according to the COST 323 (2002) method, are shown in Table 2. The tests were performed under full reproducibility conditions (R4) and limited environmental reproducibility (II)

Table 3 – WIM performance assessment

Month (2016)	Type of measurement	n	m	s	Accuracy Class
June	GVW	1534	2,25%	3,23%	B(10)
	Group of axles	2504	2,92%	4,33%	B+(7)
	Single axles	2431	0,87%	5,19%	B+(7)
July	GVW	2867	1,88%	3,17%	B+(7)
	Group of axles	4575	2,59%	4,34%	B+(7)
	Single axle	4644	0,60%	6,36%	B(10)
August	GVW	1017	2,19%	3,32%	B(10)
	Group of axles	1649	2,78%	4,34%	B+(7)
	Single axle	1568	0,82%	5,45%	B+(7)

During this period of WIM data collection, the measurements remain between classes B+(7) and B(10), indicating that the system preserved a satisfactory performance for this type of application.

In order to provide a second verification on the quality of data used in the present study, quality checks were performed through a data quality management system, which indicates possible changes in the WIM system calibration. Figure 4 shows the WIM data quality control chart for the period between April 2016 and February 2017.

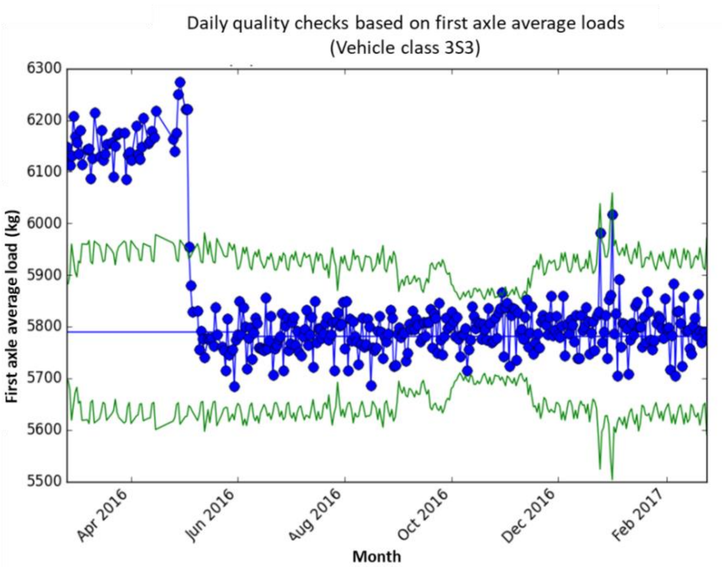

Figure 5 – WIM Data Quality Control Chart

The Data Quality Management technique used over the WIM data is described by Guerson et. al (2016). Based on the interpretation of the control chart, it shows that the WIM system weight measurements remained stable throughout the period of data collection used for the this pilot study, between June and August 2016, and also for several months after the pilot was performed. After calibration of the system, in May 2016, the control variable remained within the lower and upper limits established by the method, indicating that the weighing system was still calibrated in February, 2017.

7. Final Considerations

This pilot study has demonstrated the use of a WIM system for the design and definition of prevention strategies aiming at vehicle overload control. Over the period of three consecutive months, WIM data was collected and processed while its quality and accuracy were monitored for reliable results.

Based on the study described in this paper, a model for the Brazilian National Program for Vehicle Overload Prevention was conceived with the objective of promoting prevention processes that complement the existing enforcement instruments for overload control in Brazilian highways.

The structure of the program considers both local and international experiences, as well as particularities of the Brazilian road system. The results of the pilot application show that it is possible to apply intelligence to the processes of vehicle data collection in order to generate useful information for the elaboration of actions capable of contributing to the reduction of the overloading rates in a given location.

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Session 4 : WIM for direct Enforcement

Chair: Valter Zanela Tani (UFSC/LabTrans, Brazil)

APPLICATION OF DEEP LEARNING TECHNIQUE IN HIGH SPEED WEIGH-IN-MOTION SYSTEMS FOR DIRECT ENFORCEMENT

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Abstract

Direct Enforcement Weigh-in-motion (WIM) systems are inevitable parts for Intelligent Transportation Systems. Hence, it is essential to have reliable WIM instruments that fulfill standard specifications during operation time. To that effect, two weighing platforms were used in each lane, (3.5~4.5 x 0.98) m.

For a period of more than one year, more than 50,000 trucks from various classifications, in different weigh-station locations, had passed our WIM platforms, were stopped to be weighed statically. Axle, Group of Axles and Gross Vehicle loads of these vehicle were measured utilizing a specially designed static truck scale. So we create invaluable datasets, which in turn, made the WIM systems perform independent of vehicles' suspension system types and road surface quality.

Keywords: weigh-in-motion, data analysis, deep learning technique, direct enforcement.

Résumé

Les sytèmes de pesage à contrôle de sanction automatique sont des éléments essentiels de systèmes de transport intelligents. Ainsi il est important d'avoir des systèmes de pesage remplissant certaines spécifications durant leur durée d'exploitation. Pour cela, deux systèmes de .pesage ont été utilisés, un par voie de circulation

Sur une période de plus d'une anné, plus de 50 000 poids lourds, de différentes silhouettes et de différentes station sde pesage, ont été traités par nos systèmes de pesage pour être pesés en statique. Les poids des essieux, des groupes d'essieux et poids totaux ont été mesurés. Ceci nous . .a permis de créer des données indépendantes des suspension er de la qualité de la surface

1. Introduction

Transportation and Road Ministry of Iran is currently implementing a network of WIM systems deployed throughout the whole country consisting of more than 150 WIM systems. The main reason of using WIM systems is to measure gross, axle, and axle-group weights of trucks to improve road maintenance, infrastructure design, and load limit enforcement. To accomplish this, a national project started to install more than 150 WIM systems in main roads all over the country.

One challenge in WIM system is data analysis method. To date, different approaches have been applied to increase weigh estimation accuracy. For example, (Zhi-feng et. al, 2015) presented particle swarm optimization method to separate the dynamic tire forces contained in axle-weight signal. In order to improve precision of the WIM system data for direct enforcement, there is an urgent need for data analysis methods that can analyze massive data from weighing sensors automatically and provide axles, group of axles and gross vehicle weights accurately. Artificial intelligence techniques, such as artificial neural networks (ANNs), could be used for weight estimation and vehicle classification as well. A neural network approach was developed in (Wang & Flood, 2015) for WIM system. Through the literature review, it was noticed that ANNs are one of the most commonly used classifiers and estimator approach in the intelligent methods. Gonzalez et. al, (2003) reported that applying ANNs outperformed the traditional average-based calibration methods especially with noisy data. ANN-based approaches have been applied for dynamic weighing systems since 1998 by Bahar & Horrocks, (1998) and in many other researches (Baladrón, et. al, 2012, Lin et. al, 2015, Ru, et. al, 2010). The ANN-based approaches reported in literature for dynamic weighing systems have three obvious deficiencies:(1) The features input into neural system are extracted and selected from the measured signals of load sensors (such as load cells), largely depend on shape of the signal and the sampling rate of data acquisition system. (2) The features are selected according to velocity of vehicle passing WIM system. Characteristics of the signal are completely dependent on vehicle velocity. Thus it is necessary to adaptively mine the characteristics hidden in the measured signals to extract appropriate features out of the data. (3) The ANNs commonly developed in intelligent WIM systems have shallow simple architectures, which means having only one hidden layer in an ANN architecture; e.g. (Jiang, et. al, 2012, Lin et. al, 2015). Such simple architectures of ANN may not be able to model nonlinearities of WIM data. Deep learning (DL) technique holds the potential to overcome the aforementioned deficiencies in the dynamic weighing systems. DL refers to a class of machine learning methods, where many layers of information processing stages in deep architectures are used for classification, regression and other tasks (Jia, et. al, 2016). Deep neural networks (DNNs) is applied for sensor signal processing in WIM system. This paper proposes a novel data analysis method to overcome the above-mentioned deficiencies of the ANN-based techniques used in WIM systems. In this method, DNNs are utilized to extract features from weighing sensor (load cell) data and estimate static axle weight. First, unsupervised layer-by-layer learning is used to pre-train data and modify features. Then a supervised learning algorithm is applied to construct the best model for the WIM system. The advantages of the proposed method are summarized as follows. (1) It is able to extract adaptively dominant features from raw data without any dependency to the vehicle velocity. (2) The technique is capable of constructing the nonlinear relationships in the data. So, the proposed algorithm is expected to estimate axle load regardless of vehicle speed, vehicle suspension types and WIM site road roughness. Compared with available methods the proposed approach, is expected to obtain higher axle weight estimation accuracy to establish intelligent WIM (IWIM) system eligible for direct enforcement.

2. Deep learning

DL constructs a high dimensional function via sequences of training to model nonlinear transformations among data. The deep architectures are very large neural networks that can handle huge amounts of data. These large NNs are trained with more and more data to increase their performance. This is generally different to other machine learning techniques that reach a plateau in performance. Deep learning allows for efficient modeling of nonlinear functions. The advantage of deep hidden layers is for a high dimensional input variable, x = (x1, . . . , xp). DNN is able to identify any underlying trends such as those due to spatial repeatability and to consider them in its estimation of labeled value. The Kolmogorov-Arnold representation theorem provides the theoretical motivation for deep learning (Polson, et. al, 2017). The theorem states that any continuous function of n variables, defined by F (x), can be represented as

$$F(x) = \sum_{j=1}^{2n+1} g_j \left(\sum_{i=1}^{n} h_{ij}(x_i) \right) \tag{1}$$

Where g_i and h_{ij} are continuous functions, and h_{ij} is a universal basis, that does not depend on F. For a NN, it means that any function of n variables can be represented as a neural network with one hidden layer and 2n + 1 activation functions.

3. HS-WIM structure

An overview of different sections of the proposed HS-WIM system is shown in Figure 1. The basic structure of the HS-WIM system is composed of four main modules: (1) mechanical components, (2) electrical components, (3) software components and (4) vision components. These four modules are further defined as follows:

Mechanical module: This grouping includes the set of technologies, structures and sensors that receive vehicle axle weight data while passing the system. This section includes load receptors, weighing steel structure, weighing platforms and load cell sensors. The Load cells used in HS-WIM system have maximum error of ±0.02% for static weighing and are class C3 OIML certified. The mechanical module is statically calibrated with dead weights in the factory before installation.

Electrical module: this grouping contains the set of receiving axle load data, converting and digitizing data and pre-filtering components. This module composed of A/D converters, decimate board, pre-filter board, and data logger. All instruments of this section is calibrated in the laboratory before installation and all parts are absolutely interchangeable.

Vehicle identification module: this grouping encompasses motion detection, optical character recognition (OCR), and automatic number plate recognition (ANPR) technologies. The components in this part are such as front view camera, side view camera, IR light, white light and image analysis software.
Software programming module: this grouping provides data analyzing for axle load estimation, library, dataset creation, vehicle detection and vehicle identification techniques. Expanded overview of the proposed HS-WIM system architecture is depicted in Figure 2. The arrows connecting each of the components in Figure 2 illustrate the specific information interfaces for the modules in the architecture. The screening computer integrates data from the modules in the system to screen and identify target vehicles at the road. The data from the overloaded vehicles

and Data Center elements are sent to enforcement center. This information will be used to directly apply enforcement activities on the targeted vehicles.

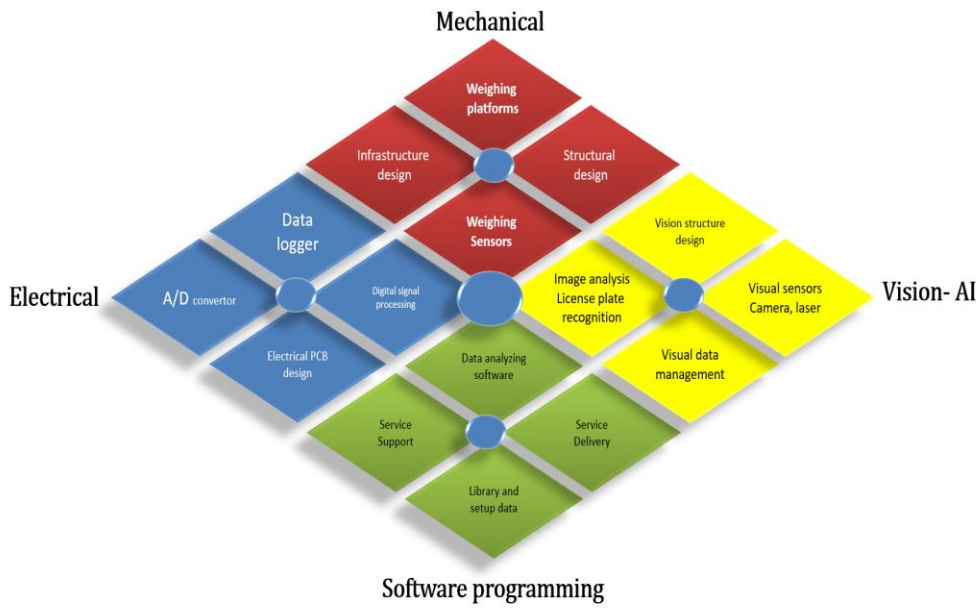

Figure 1 - Four main modules of HS-WIM system

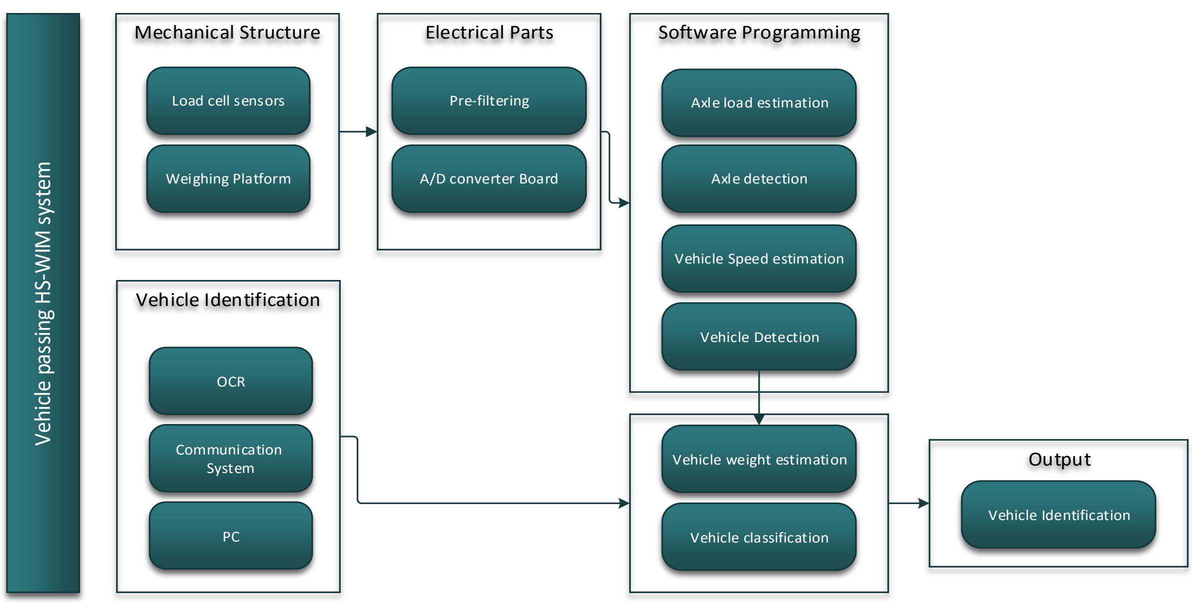

Figure 2 - Expanded hierarchical architecture of HS-WIM system

4. Deep Learning technique for WIM system

Raw data from load cells are received at 63K.Sample/sec rate. This signal may include some random noise as well as vehicle axle weight. One sample data from weighing platforms are shown in Figure 3. The amplitudes and frequencies of dynamic tire forces vary with vehicle speed, load of vehicle, the position of tire load, vehicle suspension type, tire tread type, road roughness, road inclination and so on. It is illustrated that load cell vibration due to dynamic axle impact needs some time to settle down until actual weight signal become stable. We need to estimate static axle load from load cell transient response in HS-WIM system. Since the width (in the direction of traffic flow) of scale platform is 98 cm, so the quicker the vehicles pass the shorter the sampling time and the shorter signal we have. DNNs are trained in three main procedures: (1) Clustering raw data into different clusters according to features characteristics. (2) Pre-training the DNNs layer by layer with unsupervised method called autoencoders. (3) Training DNNs with back propagation (BP) algorithm to minimize square relative error.

5. Clustering

The goal of clustering is identifying classes that all data points into each class have more similarities than data points in other collections. Clustering is the study of algorithm and methods for grouping or classifying objects. A cluster is a collection of data points which are “alike” and data from other collections are not alike (Jain, & Dubes, 1988). This study applied T-Distributed Stochastic Neighbor Embedding (T-SNE) for dimension reduction of data. T-SNE is a nonlinear dimensionality reduction algorithm used for exploring high-dimensional data. It transforms multi-dimensional data to two or more dimensions suitable for human observation. T-SNE technique was applied on Load cell signals; some clusters of features extracted from load cell signal are depicted in Figure 4. One sample result of dimensionality reduction on load cell signal is shown in Figure 5. After application of hierarchical clustering on signal, the clusters are in seven groups depicted in Figure 6. Geometrical characteristics of load cell data were used for clustering; for example, peaks and valleys amplitude ratio and frequency of data are parameters used for clustering. Then data in each cluster are used to train a DNN system separately.

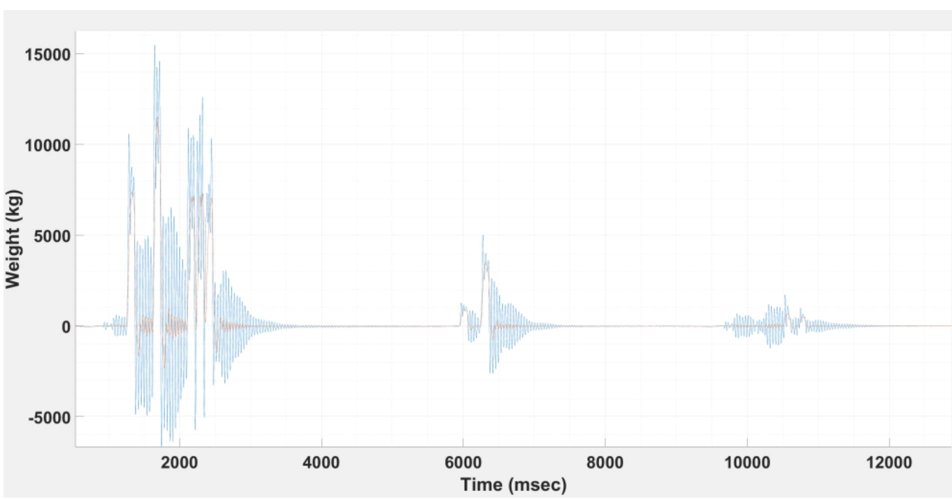

Figure 3 - Sample data from weighing platforms

6. Autoencoder for load cell signal

After clustering signals and identifying alike groups, each collection is sent to Autoencoder (AE) for subject modeling. Features extracted in each cluster are used as input to an AE. An AE is a DNN that has the same dimensions for input and output and all layers are fully connected. In the training phase, the AE is trained by using the same load cell signal as input and also output. An AE can generate highly similar output for trained data, whereas it does not for unfamiliar data.

Therefore, different test sets are used for validation and cross-validation processes. Figure 7 illustrates the proposed method for AE which is a seven-layer AE with one input layer, five hidden layers, and one output layer. Output of each layer is used as an input to the next layer. The training steps continue until the sixth layer autoencoder is trained and the output layer provides the organized features for the load cell signal. In the proposed AE, the pre-training via encoder and decoders helps DNNs learn multiple nonlinear relationships among extracted features. Then the fine-tuning process helps the DNNs estimate static axle weights from load cell signals.

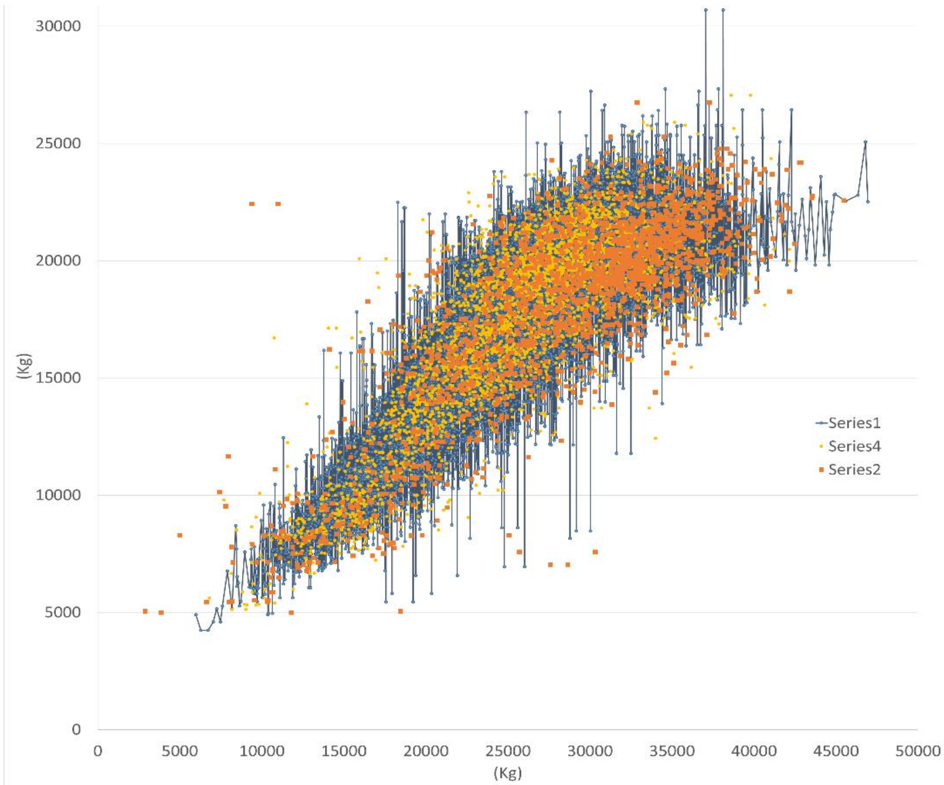

Figure 4 – some clusters of features extracted from load cell signal

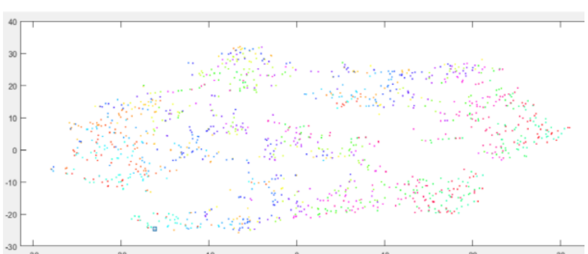

Figure 5 – T-SNE on load cell signal

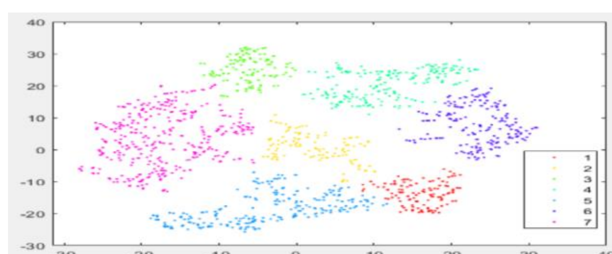

Figure 6 – clustering load cell signal

7. DNN construction for HS-WIM system

In a HS-WIM system, the relationship of speed, platform vibration, pavement roughness, pavement inclination, vehicle's suspension type and other factors is very complex and nonlinear. So, it is difficult to identify a function and specific mathematical expressions to represent static weight analytically. Therefore, in this study a DNN algorithm was proposed to predict the nonlinear relationships among those.

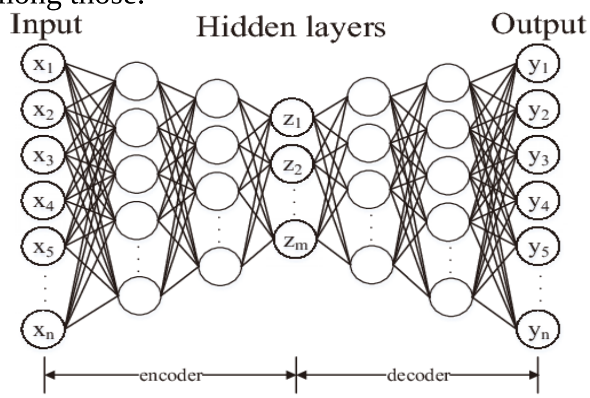

Figure 7 – Auto encoder architecture used for unsupervised learning of load cell signal

8. Data description

The training sets of labeled data (known reference static axle loads) were prepared from HS-WIM system installed in Ardestan in two lanes. More than 50000 random vehicles of 2-, 3-, 4-, 5-, and 6-axle trucks were weighted statically using reference instruments. Weighing instruments used to determine the static reference vehicle axle loads are OIML R76 certified. Therefore, reference static axle loads are all measured with less than ±1% error. So, we had a dataset of more than 300,000 axle weights with known referenced value. We used 70% of this data set for training of DNNs and 20% of data for test set and 10% for cross-validation of proposed DNN. Some of sample tests and reference axle weights are depicted in Table 1. Platform data (load cell signal) for all vehicles passing WIM system are recorded in text files. These files are analyzed off-line for training of DNN.

Table 1 – sample of referenced vehicle tests using static reference scale

				Static Weight (kg)			
Date and time	Speed (km/h)	Lane	Vehicle class	Group Axle1	Group Axle2	Group Axle3	Total Weight
20170814-125442	62	1	12	7200	12650	21890	41740
20170814-125449	57	1	13	5800	15600	20670	42070
20170814-125652	91	2	12	6780	12050	21550	40380
20170814-125709	78	1	13	6380	16070	20960	43410
20170814-125710	75	2	12	6910	11290	22430	40630
20170814-125829	74	2	7	7070	19920	0	26990
20170814-125838	70	3	12	7060	9950	22510	39520
20170814-125847	44	1	13	4350	14420	14900	33670
20170814-125853	52	1	13	6190	15310	14160	35660

9. Training of DNN

By using HS-WIM systems, the amount of each axle load, the total gross vehicle weight, and also the Equivalent Single Axle Load (ESAL) for each vehicle are estimated very accurately. Load cell signals for all 300,000 static axle weights are recorded then are pre-processed for feature extraction. After that data are sent to AE. Output from AE are sent to DNNs for training. Training process are repeated many times until the least square relative error is attained. The network is composed of five layers 23 nodes in input layer and 20 nodes in hidden layers and one node in output layer. Tangent hyperbolic function (tansig) was used in hidden layers and purelin function in output layer. In the proposed DNNs, Levenberg-Marquardt (lm) algorithm were used for training. Because the mean square error in lm algorithm decreases much more rapidly with time than other algorithms. Sometime training time would take half a day to be completed because of the big data sets we have. Each trained net is also tested on test sets and validation sets. Finally, the net with the least relative error (the highest accuracy) on train set, test set and validation set is chosen. Training results are depicted in Figure 8.

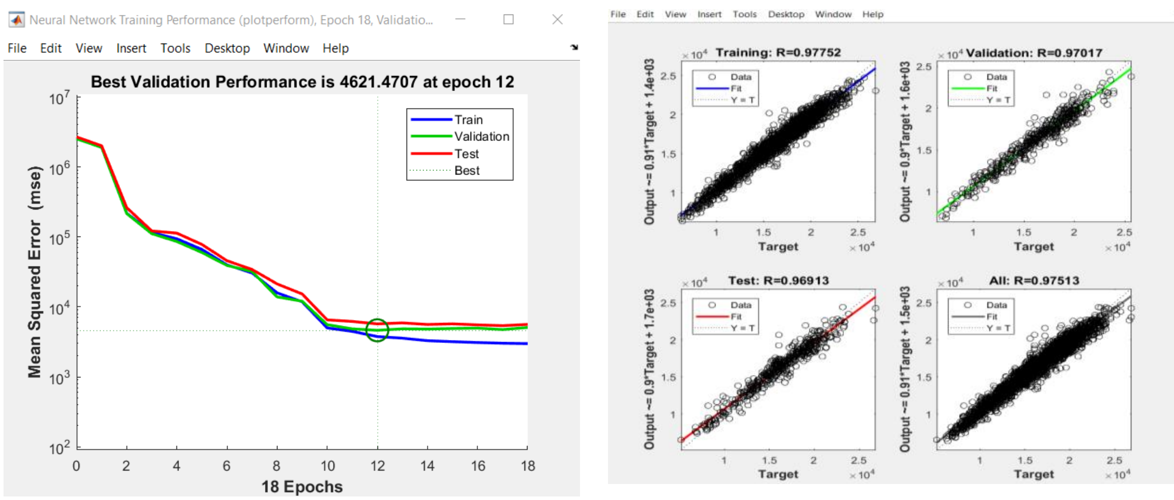

Figure 8 - regression results

10. Performance of DNN on HS-WIM and results

10.1 HS-WIM layout

Figure 9 shows layouts of the proposed HS-WIM systems and automatic number plate recognition system. This figure illustrates that there are two platforms installed next to each other with 7 cm space in each line; platform A1, platform B1 for fast lane (line 1) and platform A2, platform B2 for slow lane (line 2).

10.2 Field test results

Initial experiments with varying network depths showed that deep nets work better than shallow ones. Therefore, among different architectures of deep nets a DNN with 9 layers and tansig activation function has the highest accuracy in axle weight estimation. We trained two main collections: (1) high-speed load cell signals. (2) normal-speed load cell signals (shown in Figure 10). In high-speed cases, number of extracted features are less than normal-speed ones. But speed is not considered as an input to the DNN. The proposed technique was applied on 300,000 data of different random trucks from the traffic flow. All this data is from Ardestan HS-WIM site. Some of the test results are shown in Table 2. This table shows static reference weights, dynamic estimated weights and percentage of error between them. Performance of the trained DNN was calculated as mean square error (mse) on each data set. For the best results on the test and validation sets mse was 2.26 E7, 3.15 E7 respectively. This technique is working almost one year in Ardestan WIM site. Periodic tests are performed for this WIM system and all of the test results are within L (5) accuracy class and consequently eligible for direct enforcement. The suggested DNN technique is applied on other HS-WIM sites such as Delijan, Esfehan, Naeen and many other sites in the country. The proposed DNN technique would be fine-tuned for new WIM-installation sites using 200 test data. Thus, this approach is independent from road roughness and pavement conditions. The proposed WIM system is capable of recognizing driver behaviors such as rapid accelerating or decelerating. Using two platforms with 98 cm width (in direction of the traffic flow) made it possible to have complete tire contact-patch and tire load distribution. So, amount of damage caused by vehicle axle loads (ESAL) could be accurately calculated in this system. The results show that using two platforms in each lane increases accuracy of the axle weighing dramatically. It compensates for vehicle suspension vibrations and road unevenness as well. It seems that DNN is capable of managing big data efficiently from several load sensors. The suggested DNN is able to identify any underlying trends such as those due to spatial repeatability and to consider them in its estimate of static axle weight. The offered HS-WIM system is complied with OIML R134.

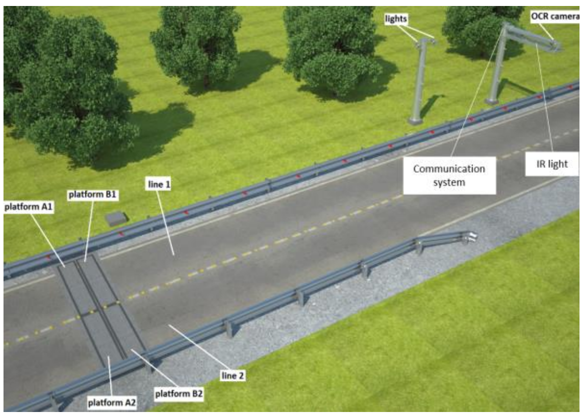

Figure 9 - HS-WIM system layouts

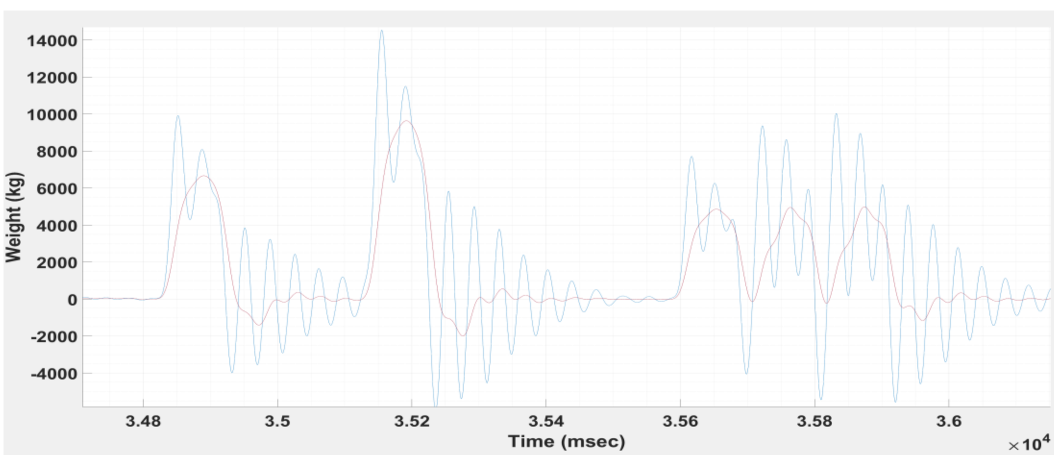

Figure 10 - some of typical load cell signals received from HS-WIM system that are inputs to AE and DNN

11. Conclusion

This research presents a deep neural network technique for dynamic vehicle weighing. The effectiveness of the proposed method is verified using five datasets from various HS-WIM sites in different places in Iran highways. These datasets contain more than 300,000 axles with known referenced weights. All these static weights are measured using control weighing instruments (static truck scales) which are certified according to OIML R76. Reference vehicles are various trucks randomly chosen from the traffic flow. All this labeled data is used for unsupervised and supervised learning processes. The results of these datasets shown that the proposed method is able to weigh axle loads of different trucks with L(5) accuracy. Every mechanical and electrical parts of HS-WIM system are interchangeable and the proposed DNN approach is able to identify any underlying trends and nonlinear relationships among characteristics of the system. Thus, the proposed method is the least dependent on road roughness and pavement conditions and L(5) accuracy class is obtainable with installing this WIM system anywhere other than current positions. The offered HS-WIM system is complied with OIML R134. In the proposed method, DNNs are trained using Levenberg-Marquardt (lm) algorithm. Because the mean square error in lm algorithm decreases much more rapidly with time than other algorithms.

Table 2 – some results from performance of the proposed DNN on HS-WIM: comparison of estimated axle weights and static weights are shown as relative error (% of error)

Speed (Km/h)	Vehicle class	Static Weight (kg)				Weight in Motion (kg)				% of error			
		GAX1	GAX2	GAX3	Total weight	GAX1	GAX2	GAX3	Total weight	GAX1	GAX2	GAX3	Total weight
68	13	5680	8680	9650	24010	5591	8514	9799	23904	-1.57	-1.91	1.54	-0.44
83	4	5660	9980	0	15640	5573	10640	0	16213	-1.54	6.61	0.00	3.66
78	13	5820	11720	11940	29480	5976	12360	12264	30600	2.68	5.46	2.71	3.80
75	4	5180	6420	0	11600	5322	6294	0	11616	2.74	-1.96	0.00	0.14
70	13	6370	18650	13360	38380	5935	20018	13197	39150	-6.83	7.34	-1.22	2.01
63	12	6370	12070	20510	38950	6263	11706	21110	39079	-1.68	-3.02	2.93	0.33
54	13	6620	17260	20240	44120	6342	17333	20325	44000	-4.20	0.42	0.42	-0.27
69	13	6540	14780	15690	37010	6593	14601	16755	37949	0.81	-1.21	6.79	2.54
72	7	6470	21960	0	28430	6890	21796	0	28686	6.49	-0.75	0.00	0.90
61	4	6380	13230	0	19610	6694	13394	0	20088	4.92	1.24	0.00	2.44

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WEIGHT ENFORCEMENT NETWORK OF HUNGARY

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Abstract

After two years of legislative preparation, the live testing of National Axle Weight Measurement System (TSM), featuring 100+ control sites nationwide on the roads of Hungary, has started in early 2018. This paper aims to present a brief summary of the technological and regulatory background of a large-scale integration of High Speed WIM systems, from the stage of type approval, to the first automatically generated administrative fines for weight limit violation. With each of the co-authors taking on a different role during the implementation (incl. customer and legislator, carrier and integrator) this paper presents a wide-angle case study of a project, that is currently unmatched in scale, when it comes to the application of Weigh-In-Motion technology for legal purposes in the European Union.

Keywords: automatic weight enforcement, WIM legislation, metrological certification

Après deux années de travaux préparatoires juridiques au début de 2018, a commencé la période d'essai du réseau de national hongrois de mesure des poids sur essieux (TSM) - avec plus de 100 points de mesure à travers le pays. La présente étude donne un bref aperçu du contexte technique et juridique de l'intégration à grande échelle du système HS-WIM, à partir de l'approbation de type jusqu'à la délivrance de la première décision de contrôle sanction automatisé pour les véhicules surchargés. Tous les co-auteurs ont participé à différents rôles dans la mise en œuvre du système (client, législateur, intégrateur, transporteur, tous sont représentés). Ainsi, l'étude de cas donne des informations complètes sur ce projet, qui utilise la technologie de pesage en marche (Weigh-In-Motion), qui est un système unique dans l'UE pour les pesages conformément aux dispositions légales.

Mots-clés: contrôle sanction automatisé, législation de pesage, certification métrologique

1. Introduction

Following the example of the Hungarian road toll system (HU-GO[1]) and the intelligent road checkpoint system (VEDA[2]) operated by the police, the new weight enforcement network will also utilize the 'principle of objective liability'; meaning that in case of a vehicle- or axle-weight limit violation, the administrative procedure is initiated against the transport operator instantly. Legally binding administrative decisions are generated via the exact same way as a fine for speeding, or a fine for unauthorized usage of toll-roads. This means, the margin of error is very small when it comes to vehicle identification and the evaluation of WIM measurement data. In order to reach the unprecedented requirements of the enforcement network, all parties had to work in close cooperation, including the contractors, the regulator, professional representatives of transport associations as well as a great number of technicians, drivers and metrologists involved. Our focus is on the various obstacles, that the integrator, the customer (transport authority) and the administration of metrology had to face meanwhile creating WIM certification procedures that are metrologically acceptable, practically feasible, and ready to handle issues specific to the autonomous nature of the enforcement. The networked WIM sites (figure 1) and their corresponding road surveillance infrastructure are detecting over 40 million events monthly. Such a vast amount of data shall be collected and processed within the enforcement network in a way that effectively supports traffic control task-groups on site with real-time alerts of suspected infringements, is fully compatible with all related governmental IT systems and law enforcement databases, meanwhile respects applicable information privacy and data protection acts. Besides the study of the crucial milestones of the project, the authors give a statistical overview of weighing data in correlation with the main patterns of road freight transport in Hungary.

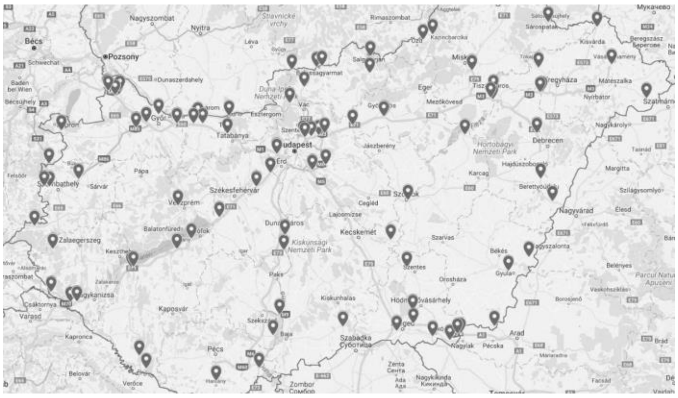

Figure 1 – Location of WIM sites in Hungary (Google Maps, 2018)

2. Legislation of TSM

2.1 The proposal of the project

For many years, operating overloaded cargo vehicles has been a ‘low-risk high-yield’ practice in Hungary, since carriers could achieve remarkable competitive advantage with a very low chance to be randomly chosen for on-site measurement by mobile inspection units. Static weight bridges present a much better inspection coverage, but they inflict significant time loss to lawful carriers and are easily avoided by the less lawful ones. Project TSM has achieved a

[1] Distance-based electronic toll system for heavy goods vehicles on the toll sections of speedways and main roads, introduced in 2013 www.hu-go.hu

[2] Complex roadside speed-cam and control system, introduced in 2015

major increase in coverage and enforcement efficiency, featuring 107 WIM stations monitoring 274 lanes with approximately 1500 quartz sensors installed. The development was financed (for over 90 Million EUR) by domestic budget and managed by the public-sector consortium of National Transport Authority of Hungary and the National Toll Payment Services Plc. Decision-makers have been guided by the well-known goals of the proposed solution: improvement of *road safety* (as overloaded vehicles pose an increased risk and severity of accidents), preserving the general *condition of the roads* (as overloaded axles significantly deteriorate the public roads network; its annual maintenance cost is larger than the total investment of project TSM), create a *fair competitive environment* (as law-abiding businesses had to face a market distorted by carriers violating regulations for higher profit). The existing infrastructure of the toll enforcement system[1] provided a cost-efficient method of implementation, utilizing its power-, communication-, and processing capabilities. The system is capable to detect and measure all types of vehicles, including cars, minivans, trailers, motorcycles, but the current regulatory background does not extend to said classes, when it comes to direct enforcement. These drivers still have to comply with applicable weight regulations and may be subject to conventional inspection by authorities.

2.2 Regulatory background

Although the paradigms (i.e. size and weight limits) of freight traffic control are unchanged, the introduction of TSM into the Hungarian legal system was a major task from legal and professional point of view. The existing regulatory processes for the case of objective liability have been extended (Government Decree 410/2007) with automatic weighing and its respective exclusions. A set of obsolete regulations needed to be modernized, such as the revision of Gov. Decree 156/2009 (VII.29.) (table 1) to meet today's requirements and align with EU regulations.

Table 1 - Summary of fines imposed on overweight vehicles (approximate values)

Excess weight		Fine (~EUR)
Vehicle over maximum permissible gross weight	… < 5%	150 €
	5 % ≤ … < 10 %	300 €
	10 % ≤ … < 20 %	600 €
	20 % ≤ … < 30 %	1 000 €
	30 % ≤ …	1 500 €
Vehicle with axle over maximum permissible axle weight	… < 5%	150 €
	5 % ≤ … < 10 %	300 €
	10 % ≤ … < 20 %	600 €
	20 % ≤ … < 30 %	1 000 €
	30 % ≤ …	1 500 €
Deliberate avoidance of control		300 €

The listed fines are independent of the method of uncovering the infringement: onsite control or automated control. An 8-hour calculation rule is applied in case of WIM, since the operator or driver might not be immediately aware of the infringement. The highest degree of fine is to be imposed within the period of 8 hours. All control bodies are obliged to record their imposed, weight-related fine in the TSM system, thus eliminating repeated penalties. A new type of administrative fine for deliberate manipulation of the weight results or avoidance may be imposed on operators, whose trucks repeatedly hinder in-motion measurement (i.e. going off-road) for no apparent reason.

2.3 Type approval of ARH-WIM

Following multiple practice sessions of calibration and certification procedure (as described in chapter 3.2) and the simulation of various failure events, type approval for ARH-WIM has been issued in February 2017, specifying the following metrological parameters:

- accuracy class for gross weight: 5; 7; 10
- range of measurement (gvw): 1.000 kg to n*20.000 kg (n = axle nr.)
- accuracy class for axle weight: E; F; G
- range of measurement (axle): 3.000 kg to 20.000 kg
- verification interval: d = 100 kg
- speed range: 15 km/h to 150 km/h.

The listed accuracy classes and associated tolerances are in compliance with OIML-R134 (2006). As an integral part of the type approval procedure, the effects of erratic driving behavior and special cargo types (bulk load, liquids - figure 2) have been simulated as well under full road closure. The test involved 3 fuel tankers – each with different load level – 1 trailer truck filled with grain (bulk) and 1 fifty-seat bus. The test has been observed by representatives of carriers' organization.

Figure 2 – Axle load measurement of special reference vehicle (fuel tanker)

The results of the experiment showed that all measurements marked as *valid* were within the operational error limits as the WIM system detected:

- 10 out of 10 events as *invalid*, when the driver applied intense braking on the sensors;
- 6 out of 10 events as *invalid*, when the driver suddenly accelerated on the sensors;
- 0 out of 10 events as *invalid*, when consistent driving behavior was followed.

Consequently, none of these cargo types have been excluded from weight enforcement, however domestic fuel carriers, bulk loads and buses obtain additional allowance for axle weight limits after a free registration of the operator. Tanker's cylindrical shape can be reliably identified by 3D vehicle laser scanners mounted above WIM sites (figure 3).

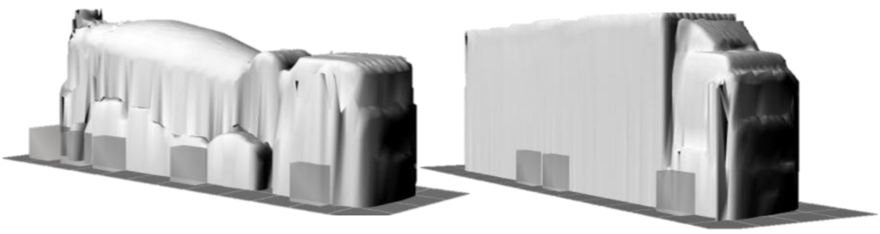

Figure 3 – 3D imagery of different trailer superstructures

2.4 Extension of road control methodology

The Roadside Control Information System (KEIR) – built on the framework of TSM – enables complex roadside- and site-inspection, covering the entire spectrum of control, featuring two-way connection with official databases of multiple authorities. KEIR provides information for road control officers, regarding the vehicle (M.O.T. inspections, insurance validity, exemptions), the driver (qualification, driving license, personal data register) and the operator (activity license, penalties, debit, etc.). Control personnel are able to log in to a set of WIM stations and receive real-time alerts. Roadside control is supported with mobile ANPR cameras and portable VMS[3]. KEIR automatically generates reports, decisions and related documentation and incorporates an electronic payment platform for handling on-site payments. Resulting data is transferred to back-office in case the administrative procedure continues.

3. Implementation of TSM

This chapter provides a brief review of the official documentation published (or approved) by the Metrology and Technical Supervisory Department of the Government Office of the Capital City Budapest. Original type approval and full certification procedure *HE 11/2-2017* are available online at *http://mkeh.gov.hu/meresugy/HE-list*.

3.1 Layout and specification of WIM network

Sensor arrays are installed in two basic configurations:

- 2 sensor rows - used for preselection, calibrated for weighing;
- 3 sensor rows - used for direct enforcement, certified by a notified body.

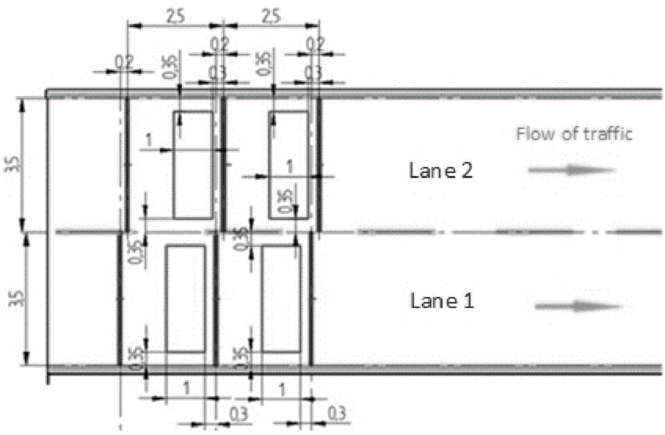

Figure 4 – Typical single-line layout featuring 12 quartz sensors and 4 loops

Quartz sensors are installed in the full width of the road (including emergency lanes) in a single line (figure 4) or offset, depending on available lane width. The system is prepared to measure vehicles passing in-between two parallel lanes.

WIM units are located in roadside cabinets equipped with door opening detection and connected to the gantry via protective tubing in order to prevent sabotage attempts. Measurement-critical hardware components are locked and sealed by the assigned regional office of metrology, the data-label and printed reports containing calibration constants are placed inside the cabinet, bearing a unique validating sticker. Preceding the installation, road surface (and in some cases

[3] Variable-Message Sign mounted on light trailer, capable of remote operation

the base layer too) has been replaced in order to meet 'Class I – Excellent' quality parameters stated in COST 323 specification, providing appropriate geometric and mechanical conditions for high accuracy measurement.

3.2 Metrological procedures

3.2.1 Certification for weighing

Initial verification session included the certification of 189 lanes and calibration of 85 lanes for weighing, with over 1000 measurement protocols issued. The immense logistical task has been carried through with simultaneous operation of five heavy goods vehicles, carrying etalon weights non-stop between August 2017 and January 2018 in the following load-configurations:

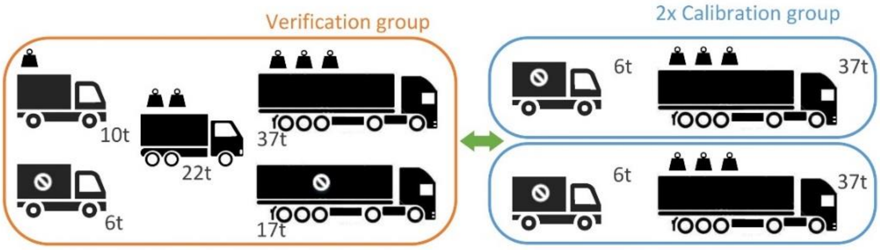

Figure 5 – Reference vehicle configurations

Calibration groups of two vehicles (representing the lower and upper end of the weight range) were used for initial sensor calibration, and for the verification of preselection WIM stations. Verification groups of five vehicles (representing the whole spectrum of weigh range) were used for metrological verification of direct enforcement WIM stations. The reference axle weight values have been measured by portable weighing system (3+3 times in both directions, supervised by representative of the notified body) and then corrected by gross weight value of a certified weight-bridge as described in annex A.9.3 of OIML R134 (2006). Drivers logged the current mileage and were obliged to refuel on every day of verification to restore their original load condition. Verification vehicles are required to undertake at least 5+5+5 test runs at three different speeds. To acquire a certification on the basis of national regulation, 90% of WIM measurements – gross weights and axle weights respectively – shall fall within MPE of verification (table 2) and 10% shall fall within MPE of operation. Metrological certificates are valid for two years or until the re-calibration of the WIM site. Vehicles of a calibration group were making a total of 5+2 test runs only at two different speeds at stations used for pre-selection.

Table 2 – Cumulative results of successful verification runs on 107 WIM sites

Site configuration		3 sensor rows, asphalt surface	2 sensor rows, asphalt surface	2 sensor rows, concrete surface
Total nr. of sites & **lanes**		74 / **189**	31 / **77**	2 / **8**
Road condition (COST)		Excellent	Good	Good
Total nr. of test runs		9 523	1 115	124
MPE (%)	gross weight	5% or $2 \cdot N \cdot d$ ** 2,5% or $N \cdot d$	7..10 %	10 %
	single axle	8% or $2d$ ** 4% or d	11..15 %	15 %
	axle group	8% or $2 \cdot n \cdot d$ ** 4% or $n \cdot d$	11..15 %	15 %

Mean Error (%)	gross weight	-0.29 %	-0.44 %	-1.18 %
	single axle	-0.58 %	-1.12 %	-0.79 %
	axle group	0.35 %	0.57 %	-2.03 %
Std. Deviation (%)	gross weight	1.66 %	2.08 %	1.77 %
	single axle	2.58 %	3.27 %	3.15 %
	axle group	2.79 %	2.81 %	2.26 %

where N = nr. of axles; n = number of axles within axle-group; d = verif. interval; **: *in case of initial verification*

It is important to note, that – for reason of comparability of different layouts – only the results of successful procedures are presented in this chapter (table 2, Figure 6), meanwhile test runs from unsuccessful verification attempts have been discarded. Statistical dispersion of measurement error of gross vehicle weight is characterized by 2.0..2.5% interquartile range (IQR), with sites featuring only two sensor rows and lower road quality classification having usually +0,5% higher IQR as seen in the boxplot below (Figure 6). The boxplot covers a specific subset of reference vehicles that were present at the verification of both certified and non-certified (preselection) stations, therefore unloaded vehicles are excluded. Presented dataset should be considered as a base of comparison of site-layouts rather than representative benchmark of quartz technology.

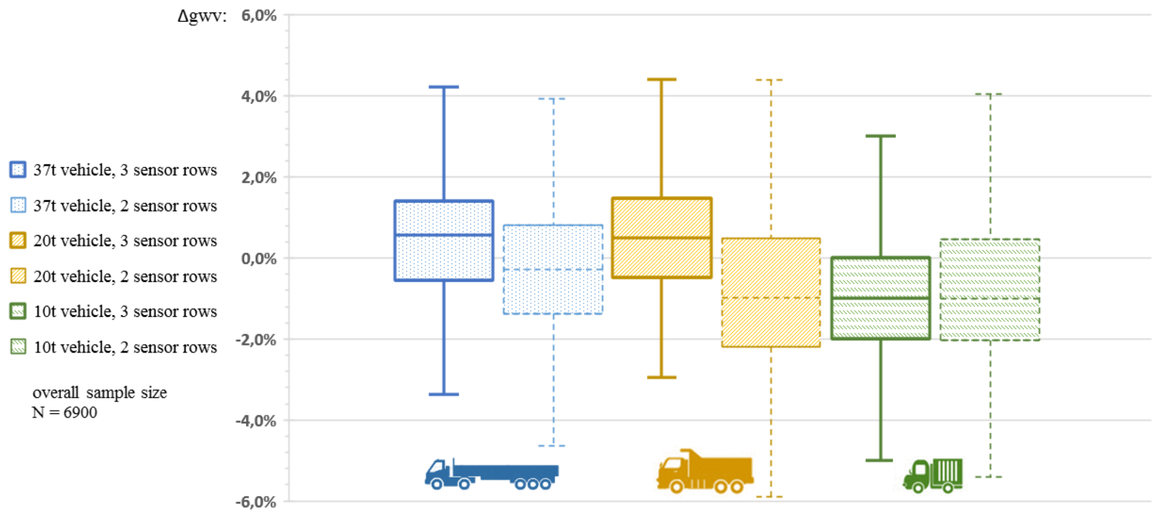

Figure 6 – Distribution of relative error for gross weight of loaded reference vehicles

3.2.2 Certification for axle distance measurement

The most important role of wheelbase measurement in enforcement aspects is the reliable identification of axle-groups and different axle-group classes. Every WIM site has passed a calibration procedure by the integrator, that includes 7 passes (at two different speed levels) of a five axle semi-trailer truck, resulting in 21 measurements per lane. Equation (1) describes the required accuracy (Maximum Permissible Error) for axle distance measurement.

$$MPE(d) = \begin{cases} \pm 50mm & | \ d \leq 2m \\ \pm 2{,}5\% & | \ d > 2m \end{cases} \qquad (1)$$

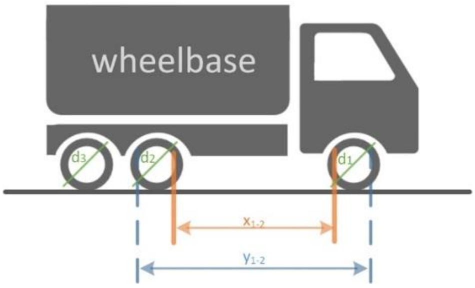

Figure 7 – Reference wheelbase measurement

Reference data have been calculated as the average distance – $X_{1,2}$ measured between inner rims, $Y_{1,2}$ measured on outer rims – on both sides of the vehicle to correct axle paralellity error and wheel ovality (figure 7). During initial verification period N=6100 axle distance measurements have been registered for the exact same semi-trailer, featuring a standard (d=1310 mm) axle group of three axles. The following characteristics of variance[4] have been observed:

- maximum error +15mm (positive difference) and -21mm (negative difference);
- 85,0% of measurements with less than $\pm$10 mm error (919 events over this limit);
- 97,4% of measurements with less than $\pm$15 mm error (161 events over this limit);
- 99,97% of measurements with less than $\pm$20 mm error (2 events over this limit).

3.2.3 Certification for vehicle speed measurement

Due to the fact that the WIM system produces legally effective weight data only within a certain speed-range (15-150km/h in our case), the operator requested the system to be calibrated for speed measurement as well. Equation (2) describes the required accuracy (Maximum Permissible Error) for vehicle speed measurement.

$$MPE(v) = \begin{cases} \pm 5\ km/h & |\ v \leq 100\ km/h \\ \pm 5\ \% & |\ v > 100\ km/h \end{cases} \tag{2}$$

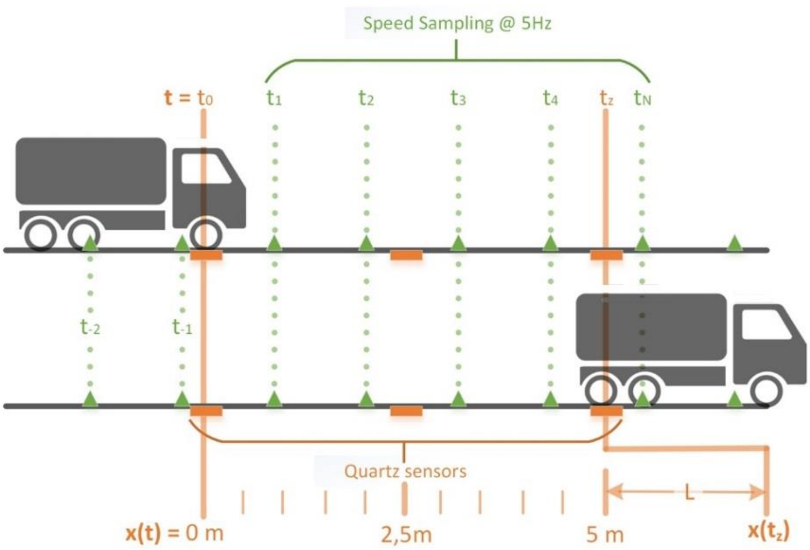

Figure 8 – Average speed measurement of the reference vehicle

[4] Expanded uncertainty (with coverage factor k=2) is 6.2 mm due to thermal expansion, inherited uncertainty of etalon, human readout error, non-parallel measurement, etc.

Reference speed have been logged by a high precision GPS unit – certified for self-speed measurement – mounted on the calibration vehicle (figure 8). Its instantaneous speed records are averaged between the time when the first axle reaches the first sensors (t_0) and when the last axle leaves the last sensor (t_z). Speed calibration includes a total of 6 passes with three different speeds. The calibration of the sites suggests, that WIM speed measurement error is below 1,2 km/h[5] and the main source of deviation is that the displayed WIM speed gets rounded down to the nearest integer value. Third sensor row had no significant impact on accuracy.

3.3 Data Quality Assurance

Beyond the certification of WIM sites, generating legally effective data from measurements on remote and open locations – such as public roads – requires continuous monitoring and QA activity on the operator's part. Each event goes through the following multi-layer verification procedure to exclude the possibility of an unjustifiable fine.

- *Recognition of effects influencing weight results:* This built-in function of the WIM unit is commonly used to mark events featuring unaccustomed driving behavior, errors in sensor signals or simply the exceedance of the certified measuring range.
- *Visual inspection:* The operator in cooperation with the road management company is required to check the WIM sites at daily frequency and intervene in case on-site conditions deteriorate (e.g. cracks on road appear, snow or spoilage pile up near the sensors).
- *Confidence:* In order to assess the reliability of weight results, confidence level is determined by the average relative deviation of the sensor's individual measurement data compared to the average wheel load (uniformity of WIM data in a single wheel's path) and also determined by the axle weights (loading profile) of the measured vehicle compared to the statistical profile belonging to the same vehicle class and axle configuration.
- *In-Network-Comparison:* Due to the high density of WIM sites on Hungarian road network, cross-referencing weight results of transiting vehicles – that often pass over 5+ WIM sites without interrupting their journey – would look very promising, however it is prohibited by law (privacy rights) to track a vehicle and connect events by plate number this way. This method is only applied to those hired reference vehicles who take part in the calibration and certification of the network, provided by BI-KA Logistics.
- *Periodic Inspection and Verification:* Qualified maintenance crew quarterly checks quartz sensor and loop parameters with specialized tools and measures deformation of road surface (rutting, evenness, protrusion of sensors). All certified WIM sites should pass a simplified verification procedure, that involves loaded reference vehicles of two different types, conducting a specified number of passes. This is followed by in-service recalibration if necessary. Metrological certification is considered void, if the site doesn't meet the criteria for either electronic parameters, road quality or accuracy of weight-, speed-, or axle distance-measurement.

4. Reception of TSM

4.1 Carrier's Reaction

The road transport industry faced a situation where the coverage of control rose from minimum to high-scale within a couple of months. On this occasion, broad market research has been

[5] Expanded uncertainty (with coverage factor k=2) is 1.27 km/h due to inherited error of etalon GPS unit, angle of passage over the sensors etc.

carried out by BI-KA Logistics on the reactions of different hauliers and transport companies in regards of the newly inaugurated TSM system. The first general finding was that the majority of these companies have set new internal guidelines and procedures to protect themselves. Equally importantly ranked are the ways and options to clearly articulate the liability of customers, shippers as well as the integration schemes on how to prove their right on contractual basis. Problems might occur on a broad scale: drivers are often not allowed to be present at the loading of their vehicle, nor they have the option to clearly verify the weight and correct positioning of the goods on board. Many customers are simply not used to transmit accurate data, which would be extremely important to model loading process by the dispatch personnel in advance. BI-KA has re-designed its internal procedures to assure full compliance with the new control system in accordance to the total weight and axle weight limits.

On one hand, new guidelines include methodologies and processes of proper stowage, on the other hand they define a clear set of instructions to prevent and to handle liability issues. As of 2018, annual driver training on (theoretical and practical ways of) proper stowage was initiated. During its trial phase, the TSM system has issued 5 overload notifications to the company, however since the go-live in July 2018 they have received none, indicating that aforementioned provisions were highly effective. While the hauliers, transport companies and forwarders had to initiate preparation similarly, at the same time they also had to involve customers to enhance their cooperation (i.e. submit adequate and accurate transport orders) and articulate their liability. In case the transport provider has no accurate information on hand about the goods prior to loading and no chance to verify goods received against documents – such as a weight bridge available at the place of loading – the fines will be passed on to the customer.

4.2 Summary of Live Operation

Automatically generated administrative fines for weight limit violations based on WIM data began to be sent out in July 2018. Due to the lack of comprehensive international experience in the field of direct-enforcement, various measures have been taken during the introductory period of the system, such as temporary tolerances for vehicle weight and separately scheduled activation of WIM sites. During the first 7 months of operation, 10-15% of certified sites were involved in live operation at a given time, in periodic rotation. Fines were applied on 1294 occasions, for the total value of 62.6 million HUF. This is a 5x increase compared to the five-year average performance of mobile inspection units (Figure 9).

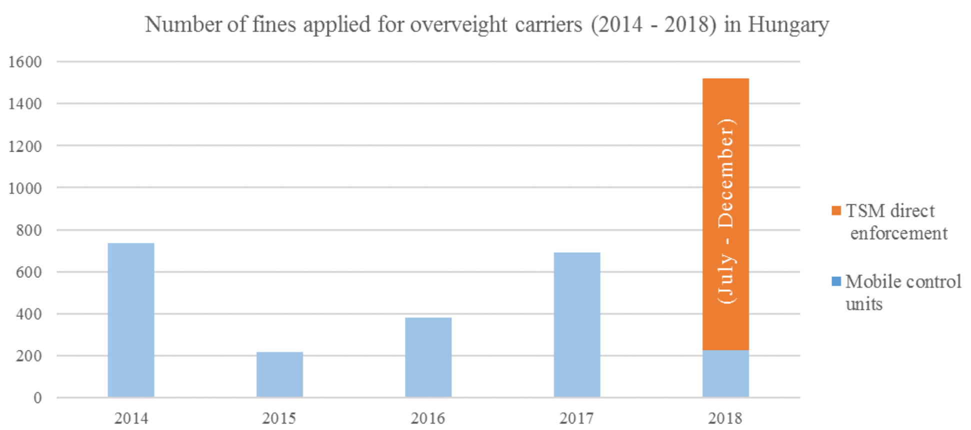

Figure 9 – Annual nr. of fines imposed on overweight trucks

5. Conclusion

Authors' intention with this case study was to give an insight on the major advantages and obstacles of operating a WIM system featuring full road network coverage and direct enforcement mode and present with an example for other national authorities contemplating similar projects in the near future. Apart from the lower acquisition costs provided by the in-bulk purchase of hardware, and a number of site specific services – such as calibration and maintenance – being conducted in a cost-efficient way, what really made the implementation financially feasible was the efficient utilization of the national road toll system. Vehicle detection, ANPR functionality, gantries with power and communication outlets were already granted on the sites, hence the duplication of roadside infrastructure could be avoided completely. Another advantage of full network coverage happened to be the potential for self-correction, and the immediate detection of sites/sensors with their accuracy suspected being below required level. A central monitoring application to exploit this potential is currently under development for TSM. Looking at the challenges: the larger the WIM network, the larger risk one has to handle to achieve and maintain public trust, which is a key factor for every governmental body managing an automated control system. One single undetected malfunction, or a sudden change in road conditions may lead to dozens of wrongful infringement fines, followed by the protest of carrier's organizations. With that in mind, the Ministry for Innovation and Technology of Hungary consciously followed a transparent approach by

- announcing an introductory period, while imposing informal administrative decisions instead of actual penalties;
- organizing an open trial-session, with all carriers' organizations invited to put the metrologically certified system to a test;
- publishing printed and online brochure, supported by TV campaign and a dedicated homepage (*www.tengelysulymeres.hu*);
- opening online user interface from which carriers can download WIM data (and photos) related to their own infringements;
- taking part in a conference series so-called *'Roadshow'*, that provided local transport companies with opportunity to express their concerns on a public forum;
- developing SMS service that provides immediate notifications for registered carriers, in case one of their trucks would be detected over its respective weight limit.

So far, these measures have proved to be an effective method to preserve the public acceptance of TSM and Weigh-In-Motion in Hungary. The next step is to review the effects and practical consequences of the legislative changes described in chapter 2.2, and to establish the aforementioned central monitoring functionality before switching all remaining sites into direct enforcement mode.

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APPROACH OF THE WALLOON LEGAL METROLOGY (BELGIUM) FOR WEIGH IN MOTION (WIM) FREE-FLOW DIRECT ENFORCEMENT



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Abstract
There are an increasing number of weigh-in-motion (WIM) direct enforcement projects around the world, always with the same challenges: how to certify a WIM system for direct enforcement? And how to be sure that this system will work effectively, without resulting in a fine for a non-overloaded truck? This was the challenge studied by the Walloon Legal Metrology in collaboration with STERELA (France). The main aim of this R&D partnership is to obtain a new certification approach which will be more in line with the needs of high-speed WIM free-flow direct enforcement, and that the Walloon approach will become a new standard or a new model for the WIM domain. To achieve this goal, the actual results of the system and some key factors influencing the measurement are presented in this article.

Keywords: Weigh-in-motion, direct enforcement, lateral position, accuracy.

Résumé
Il existe de plus en plus de projets de contrôle sanction automatisé (CSA) des surcharges à travers le monde, avec toujours les mêmes questions : comment certifier un système WIM pour faire du contrôle sanction automatisé ? Et comment être sûr que ce système fonctionnera efficacement sans imposer d'amende à un camion non surchargé ? C’est le défi étudié par la métrologie légale wallonne en collaboration avec STERELA (France). L’objectif principal de ce partenariat de R & D est d’obtenir une nouvelle approche de certification qui soit plus conforme aux besoins du CSA à haute vitesse dans le flux de circulation et que l’approche wallonne devienne un nouveau standard ou un nouveau modèle pour le secteur du WIM. A cette fin, les résultats actuels du système et certains facteurs clés qui influencent la mesure sont présentés dans cet article.

Mots-clés: Pesage dynamique, contrôle sanction automatisé, position latérale, précision.

1. Introduction

In addition to deterioration / degradation of roads and bridges (Bagui, 2013), unfair competition, and safety problems observed around the world in situations of overloaded vehicles on roads, there is another issue that each country is attempting to resolve, tracing and punishing guilty companies more effectively: the creation of a legislative framework for the direct enforcement of fines or penalties for overloaded trucks, using WIM systems. Various attempts or legal proposals exist in certain EU countries, with an accuracy level of 90 to 95% (Haugen, 2016; Jacob, 2016).

The Walloon Public Service (SPW) in Belgium is focusing on these issues with direct enforcement of weight inspections of overloaded trucks, while obtaining high-quality statistical data, with a better level of accuracy. To achieve this, the SPW is collaborating with STERELA France within the framework of a PRD OPTIWIM project, to create a pattern approval procedure for the WIM system.

Data focused on T2S3 vehicles (two-axle rigid vehicle and a three-axle draw-bar trailer) from one test station (Louvain-La-Neuve) were collected for 30 months by Sterela and SPW. During the project, collected data from the field tests were subject to various statistical processing. Certain WIM data collected were compared, by the both partners, with the static data, to check the quality of this data and the accuracy of the results with the aim to perform the algorithm calculation and improve the accuracy calculation.

The goal of the paper is to observe the influence of several key factors, pointed by Sterela, on the dynamic weighing accuracy provided by the system, such as the lateral position of the vehicle passing in their lane of traffic or the daily temperature variation.

Thanks to those key factors, the quality of the results can be improved: for instance, we obtain a confidence interval on the Global Weight above 97% for an accuracy class of 5%. With such promising results, SPW could now prepare the legislative framework for the direct enforcement based on the OIML recommendation R-134 (2006) requirements.

2. Test stations

2.1 Road surface description

Remark: This is the presumed structure, after studying the project plans and assumptions made regarding the replacement of certain layers.
A WIM weighing station was installed in an area where the roadway was built with cuttings. The landscape was disbursed about 7 meters to the right of the station. The trunk bottom of the roadway is therefore made of sand (or clay sand) with excellent natural lift. Draining sand with a minimum thickness of 20 cm is installed on this trunk floor. On this sub-foundation, 20 cm-thick lean concrete was laid, followed by 22 cm of asphalt broken down into 4 layers, as follows: 7 cm Type III[1] , 7 cm Type III, 5 cm Type I[2] and 3 cm Type II[3].
Following the COST 323 criteria, the WIM site class is II: Good.

1 Type III - corresponds to AC-20 base 3-1 (Asphalt Concrete, max. grain size: 20 mm bonded with type 1 bitumen, conventional road bitumen).

2 Type I - corresponds to AC-14 surf 1-1 (Asphalt Concrete, maximum grain size: 14 mm bonded with a bitumen type 1, conventional road bitumen).

3 Type II - asphalt type SMA (Stone Mastic Asphalt) 10-2 (max. grain size: 10 mm bonded with type 2 bitumen).

2.2 WIM Sensors layout

For the test station (Louvain-la-Neuve) interfaces with a grid of weighing sensors were installed in 2 lanes (Figure 1). A system that automatically reads the license plate number and takes a ¾ profile photo of the vehicle was also 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 (oblique black lines)
- One temperature sensor (green circle).

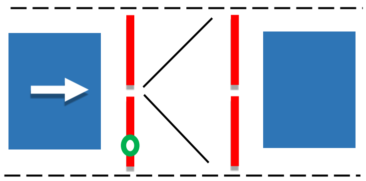

Figure 1 – Sensors layout

3. WIM accuracy: key factors

The goal of our study regarding this point is to observe the influence of several key factors on the dynamic weighing accuracy provided by the system, such as the lateral position of the vehicle passing in their lane of traffic or the daily temperature variation.

3.1 Lateral position of the vehicles

As regards this key factor, a standard vehicle is used, for which the reference weight is known. This vehicle performs on-site passes over a period of several hours, in order for the other parameters to be considered as constant (climatic conditions, evolution of the couple “sensor-roadway”) that could affect the accuracy of the measurement.

The graph below shows the error distribution according to the position of the passing vehicle for the site Louvain-la-Neuve and for the second row of piezo-quartz sensors. The test was done twice, on 8 February 2016 with a reference weight of 43 770 kg and 16 passes and on 28 February 2017 with a reference weight of 44 570 kg and 19 passes. The error is calculated between the gross weight of the standard vehicle and the dynamic weight provided by the system. Such graphs can vary completely from one site to another and from one row to another. But the general behavior for a given row remains constant over time as seen with the two test vehicles.

Without the influence of the position of the vehicle passing in its lane the error should be almost constant for all passing areas. If we consider “0” as the middle of the passing area, this is almost the case on the area from -10 cm to -70 cm (left part) but is not the case for the area from 0 to +50 cm (right part).

In accordance with the results of this test, it is therefore necessary to introduce a correction of the dynamic weight according to the position of the vehicle passing on the roadway lane.

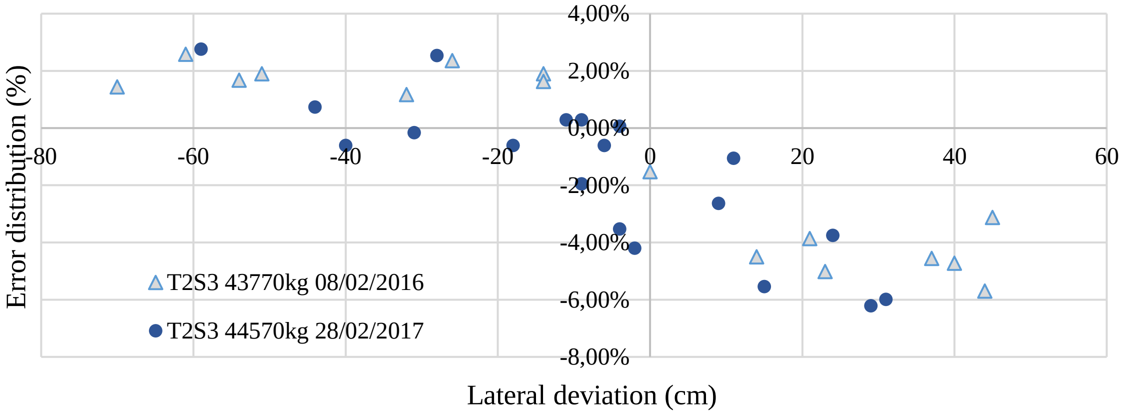

Figure 2 – Distribution of the error by lateral deviation

3.2 Temperature

A temperature sensor PT100 was placed to more or less -5 cm in relation to the road level. Temperature data was updated once per minute. In this paragraph, we analyze the temperature given by that specific sensor and put it in relation with weighed trucks.

Weight data were collected on two periods: June 2016 – August 2016 (summer) and December 2016 – February 2017 (winter). The number of weighed trucks is 47 252 for summer and 47 427 for winter with an average weight of 40 011 kg and 40 375 kg respectively. The data are plotted in Figure 3a (summer) and respectively 3b (winter) where each dot represents an average on 2 hours: for example the first dot placed on 00:00:00 for the gross weight (GW) is the average weight of the vehicles that run on the system between 00:00:00 and 02:00:00 amongst the 47 252 (and so on until 22:00:00). Correlation coefficients are respectively -0.54 and 0.11 for summer and winter between the temperature and the weight curves.

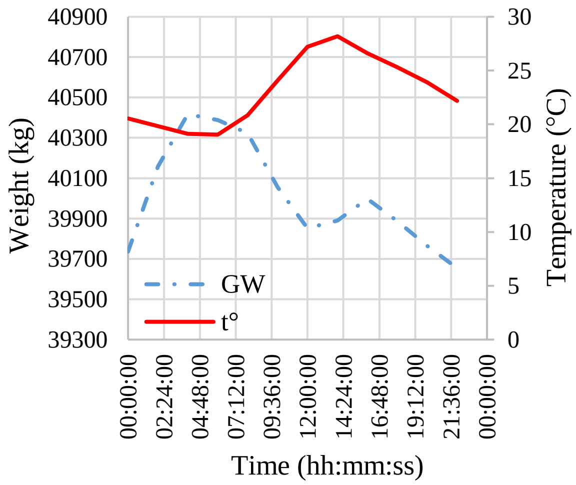

Figure 3 a – Road temperature and average weight along the day (summer)

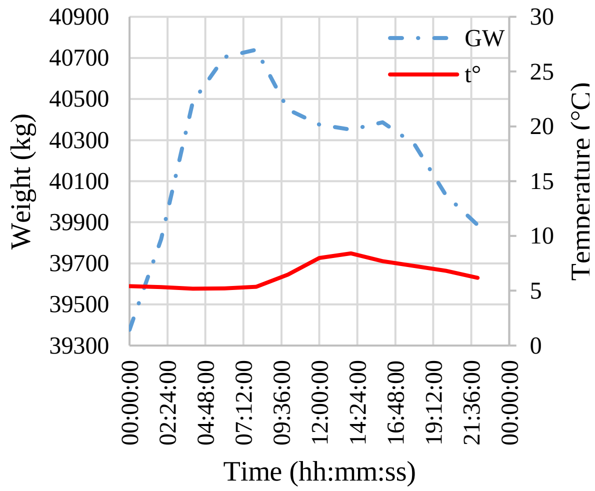

Figure 3 b – Road temperature and average weight along the day (winter)

On both graphs, we observe periods where when the temperature starts increasing the weight decreases. But in the late afternoon, we also observe that the temperature decreases while the weight also decreases.

Considering the weight curves normalized (each dot divided by the average weight) after 4 am (less than 3% of the traffic before), we calculate a maximum deviation between the curves of less than 1%. That means that the behavior of the weight (in percentage) along the day is very similar whatever the season.

Let us remark that in addition to the temperature and even if we took a large number of vehicles, the behavior of the truck drivers (truck loaded in the morning, unloaded in the evening, etc.) is probably one of the major factors affecting the average weight during the day.

At this stage, with only one sensor for the temperature, we do not push any further the investigations in a correction of the weight variation due to the temperature variation. In order to do so, we would need to implement other sensors at various depths.

4. Discussion and results

In this section, we follow Jacob (2000) and Jacob et al. (2005) in order to present the statistical results of the test station (from Louvain-La-Neuve) in accordance to the COST 323 accuracy classification.

4.1 Periods

Data were collected from early 2016 to early 2018. A calibration was made in July 2017, leading us to study the following 4 periods (P1; P2; P3a and P3b) and their corresponding repeatability and reproducibility conditions.
The algorithm runs with parameters depending on the WIM site. These parameters can be recalculated periodically. Periods 3a and 3b concern the same vehicles set but the results differ according to the change of the parameters: period 3a relates the set of initial parameters whereas period 3b concerns the set of parameters recalculated from July 6th 2017.

Table 1 - Periods of data registration with corresponding repeatability and reproducibility conditions

Period	Date Start	Date End	Calibration applied	Weighing conditions
P1	10/03/2016	29/01/2018	NO	III – R2*
P2	10/03/2016	06/07/2017	NO	III – R2*
P3a	06/07/2017	29/01/2018	NO	II – R2**
P3b	06/07/2017	29/01/2018	YES	II – R2**

* environmental full reproducibility; ** environmental limited reproducibility

4.2 Validity and sample size

Among other factors considered as key factors (see section 3), the algorithm in the HS-WIM already assigns a valid/invalid flag for each measurement. In our study, we only discuss measurements with a valid flag for which we also have a valid low-speed WIM (LS-WIM) measurement (certified system).

For each period, we detail the number of initial vehicles, the number of vehicles validated by the algorithm and the corresponding speed and low-speed weight ranges.

Table 2 – Set of the vehicles used in the calculation

Period	Number of vehicles	Number of valid vehicles	Speed range [km/h]	LS Weight range [kg]
P1	464	310	[66.6 ; 93.7]	[29 840 ; 56 020]
P2	311	208	[73.2 ; 93.5]	[29 840 ; 56 020]
P3a; P3b	153	102	[66.6 ; 93.7]	[31 210 ; 53 540]

In the light of the sample sizes (>100) and the repeatability and reproducibility conditions, we fixed the confidence interval π to 93.1 and 94.3 respectively for III-R2 (Tables 3 and 4) and II-R2 (Tables 5 and 6), as suggested by Jacob (2000).

4.3 Accuracy classes

The figures for each observed period (P1; P2; P3a and P3b) are presented in corresponding Tables 3, 4, 5 and 6 (see below) where the results are observed for the following cases: Gross Weight (GW), Group of Axles (GoA), Single Axles (SA) and Axle of a Group (AoG).

In this study, we decided to only focus on "T2S3" variants, meaning that for each truck, we had 2 SA, 1 GoA and 3 AoG. Column 5 shows the case for a given value of the confidence interval π with the value obtained for accuracy class δ (see column 6), whereas column 8 shows the variation of the confidence interval π for a given accuracy class δ (see column 7).

Table 3 – Overall statistics for the observed period (P1)

SYSTEM	Number	Mean	Standard deviation	π	δ	δ	π
Entity		(%)	(%)	(%)	(%)	(%)	(%)
1	2	3	4	5	6	7	8
GW	310	1.63	1.64	93.1	4.42	5.0	97.30
GoA	310	2.31	2.06	93.1	5.82	7.0	98.42
SA	620	0.65	2.93	93.1	5.96	8.0	99.01
AoG	930	2.31	2.71	93.1	6.79	10.0	99.71

The test station (Louvain-la-Neuve) is situated in class A(5) in accordance with COST 323 requirements, and in accordance with recommendation OIML134 requirements in class E(5) (periodical verification) and F(10) (initial verification).

4.4 Calibration

Taking into account the calibration of July 2017, the results are better (see Tables 4, 5 and 6 below): P2 (i.e. the first part of P1) has a confidence interval of 99.15% (see Table 4) for GW versus 97.30% (see Table 3) for the full period, for a statistical accuracy of 5%. This is highlighted by a comparison of P3a and P3b (same sample without and with calibration): the same entity goes up from 90.86% (see Table 5) to 98.16% (see Table 6). The shift to the left of the distribution of the relative errors between P3a and P3b seen in Figure 5 confirms this.

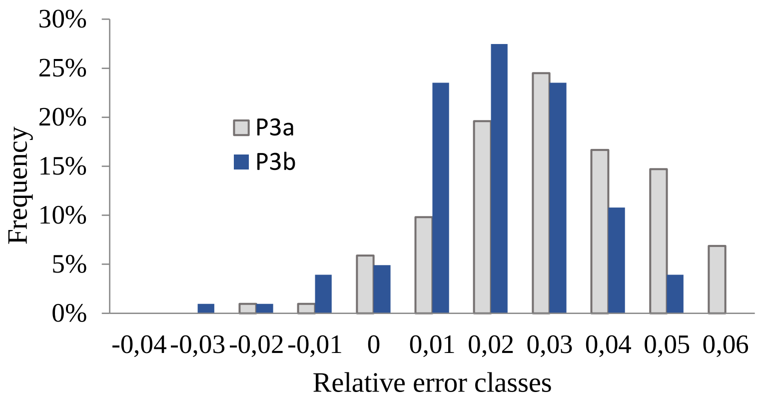

Figure 5 – Distribution of the relative errors between P3a and P3b periods

Table 4 – Statistics regarding accuracy distribution during P2 period

SYSTEM	Number	Mean	Standard deviation	π	δ	δ	π
Entity		(%)	(%)	(%)	(%)	(%)	(%)
1	2	3	4	5	6	7	8
GW	208	1.23	1.47	93.1	3.79	5.0	99.15
GoA	208	1.94	1.95	93.1	5.31	7.0	99.26
SA	516	0.24	2.87	93.1	5.77	8.0	99.24
AoG	624	1.94	2.64	93.1	6.35	10.0	99.85

Table 5 – Statistics regarding accuracy distribution during P3a period

SYSTEM	Number	Mean	Standard deviation	π	δ	δ	π
Entity		(%)	(%)	(%)	(%)	(%)	(%)
1	2	3	4	5	6	7	8
GW	102	2.45	1.65	94.3	5.42	5.0	90.86
GoA	102	3.06	2.10	94.3	6.82	7.0	95.20
SA	204	1.50	2.88	94.3	6.58	8.0	98.13
AoG	306	3.06	2.71	94.3	7.66	10.0	99.26

Table 6 – Statistics regarding accuracy distribution during P3b period

SYSTEM	Number	Mean	Standard deviation	π	δ	δ	π
Entity		(%)	(%)	(%)	(%)	(%)	(%)
1	2	3	4	5	6	7	8
GW	102	1.52	1.50	94.3	4.22	5.0	98.16
GoA	102	2.12	1.99	94.3	5.69	7.0	98.68
SA	204	0.57	2.73	94.3	5.72	8.0	99.32
AoG	306	2.12	2.61	94.3	6.58	10.0	99.80

5. Conclusions

It is necessary to introduce a correction, depending on the passing position of the vehicle in its lane. Even though Figures 3a and 3b may show links between temperature and weighing during the day evolution, in regard to the obtained data at this stage of the study, it is too early to make a correction as a function of the temperature.

Statistical results show that the studied station has an accuracy smaller than 5% for T2S3 vehicles. As such, the HS-WIM system meets the requirements of the A(5) class, in accordance with COST 323. As regards OIML recommendation R-134, the accuracy of 5% corresponds to class F(10) for the initial verification and E(5) for the periodical verification.

The results underline the necessity and the importance of a new calibration following a period of use of the system, to improve the accuracy of the measurements as shown in Tables 5 and 6. Figure 5 shows the shift to the left of the error distribution following calibration, which confirms that a new calibration is necessary after several months, to maintain or improve the quality of measurement for the direct enforcement of the weight in motion for the vehicle.

6. Acknowledgements

The authors gratefully acknowledge the Walloon State Police and Frédéric Puits from the Walloon Public Service, for collecting LS-WIM and HS-WIM data.

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




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Cerema	Cerema	Cerema	IFSTTAR

Abstract

The ongoing direct overload enforcement (DOE) research project, supported by the French Ministry of Transports (DGITM) and carried out by IFSTTAR and Cerema, aims to demonstrate the feasibility of an automated overload enforcement with adapted existing WIM technologies to be certified. This project is carried out in partnership with WIM vendors. Many trials have been carried out in lab and on the large pavement testing facility of IFSTTAR in Nantes. Sorting algorithms have been developed to identify the vehicles weighed within the OIML R134-1 recommendations required tolerances and on road trials are planned to demonstrate the feasibility of the whole system. The full paper aims to present the various road trials conducted in France in the frame of this project in terms of global organization, systems and sensors, test plans (and methodology), the really encouraging results obtained from the measures campaigns of the first phase of the project, and the organisation of the second phase.

Keywords: Weigh-In-Motion, Research project, Overloads, Direct enforcement, Road tests.

Résumé

Le projet de recherche « Contrôle Sanction Automatisé des surcharges », financé par le Ministère français en charge des transports et actuellement menés par l'IFSTTAR et le Cerema, a pour objectif de démontrer la faisabilité d'un système de contrôle légale et automatisé des surcharges à partir de dispositifs existants mais à certifier. Le projet est mené en partenariat avec plusieurs fabricants de systèmes de pesage dynamique. De nombreux essais ont été réalisés en laboratoire et avec les moyens d'essais sur piste de l'IFSTTAR à Nantes. Des algorithmes de tri ont été développés pour identifier les véhicules pesés dans les tolérances de la recommandation OIML R134-1 et des essais sur route sont planifiés pour démontrer la faisabilité d'un tel système. Cet article présente l'organisation de l'expérimentation, les différents systèmes et capteurs, la méthodologie d'évaluation et les résultats très encourageants obtenus de ces essais qui sont organisés sur une autoroute de l'Est de la France.

Mots-clés: Pesage en marche, Projet de recherche, Surcharges, Application légale de contrôle, Essais sur route.

1. Direct enforcement project presentation

The objective of the project is to study the feasibility of the direct enforcement by WIM and to prepare its certification. IFSTTAR and Cerema are in charge of the technical work packages of the project. The legal aspects are under the responsibility of the DGITM.

1.1. Contents and organization of the project

This project includes a central work package on the certification feasibility (WP1), three research and development works packages (WP2 to WP4) and a transversal work package on experimental studies (WP EX) containing experiments on road, as shown in Figure 1.

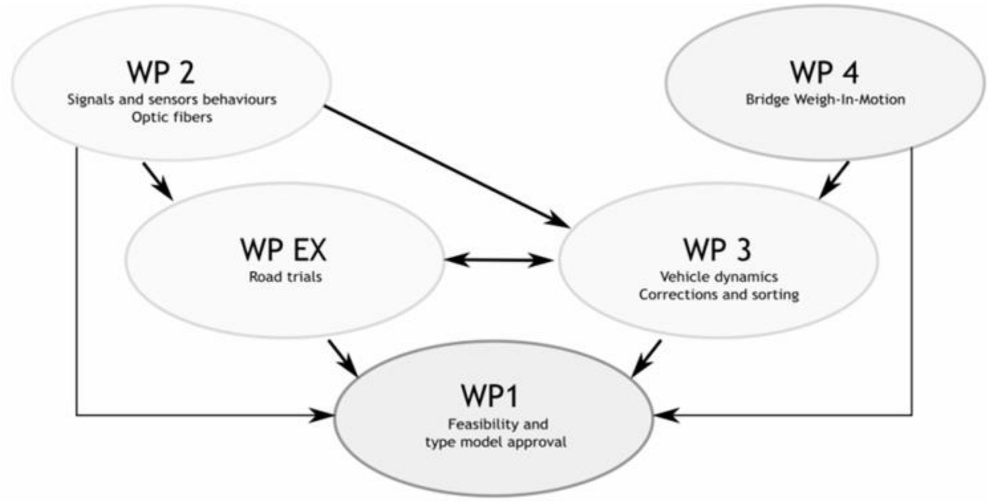


Figure 1 – Direct enforcement project organization by WPs

The 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). It will build on the French experience of speeding, spacing and traffic light crossing automated controls.

The WP2 has two subsets:

- the WP2.1 deals with sensor/pavement interactions and aims at analyzing the performance of various marketed sensors and characterizing their response in laboratory and on road controlled conditions, depending on the measurement conditions (external factors influencing load measurements),
- the WP2.2 aims at developing a new optical fibre sensor and WIM system, more efficient and less expensive than the most accurate current systems.

The WP3 addresses multiple sensor (MS-)WIM solutions for the direct enforcement, including the design of optimal arrays, methods and information processing tools to correct or sort vehicles weighed within the direct enforcement tolerances. MS-WIM aims at increasing the proportion of vehicles within these tolerances.

The WP4 aims at making a bridge (B-)WIM system operational. Such a B-WIM, including working on concrete frames bridges and orthotropic steel bridges, should meet the direct enforcement requirements. Its adaptation to other types of structures (e.g. girder bridges) is also expected.

The WP EX contains road trials, including choice and instrumentation of test sites, realization of test plans, data collection and first analysis, in partnership with the checking bodies (police, DREALs/Services transport), system suppliers and road operators (SANEF motorway company).

2. Main objectives of road trials

Road trials aim at validating, with known test vehicles, traffic vehicles and in controlled 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 correspond to the tolerances of the class A(5) accuracy of the European specifications of WIM by COST323, 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.

3. Tests site description

The trial site is located on the motorway A4, with 2x2 carriageways, near the toll-gate of Saint-Avold (figure 4) towards Metz to Strasbourg, between the towns of Boulay-Moselle and Saint-Avold (point (B) on the figure 2). This motorway is currently trafficked by HGVs and is equipped with a high speed WIM (HS-WIM) equipment for screening presumed overloaded vehicles located 7 km upstream of a control area fitted with an type approved static weighing system (figures 3). Given the position of the heat exchangers, it is possible to rotate a test truck in 35 minutes or a minimum 8 passes in one day (between the both points (A) and (C) on figure 2).

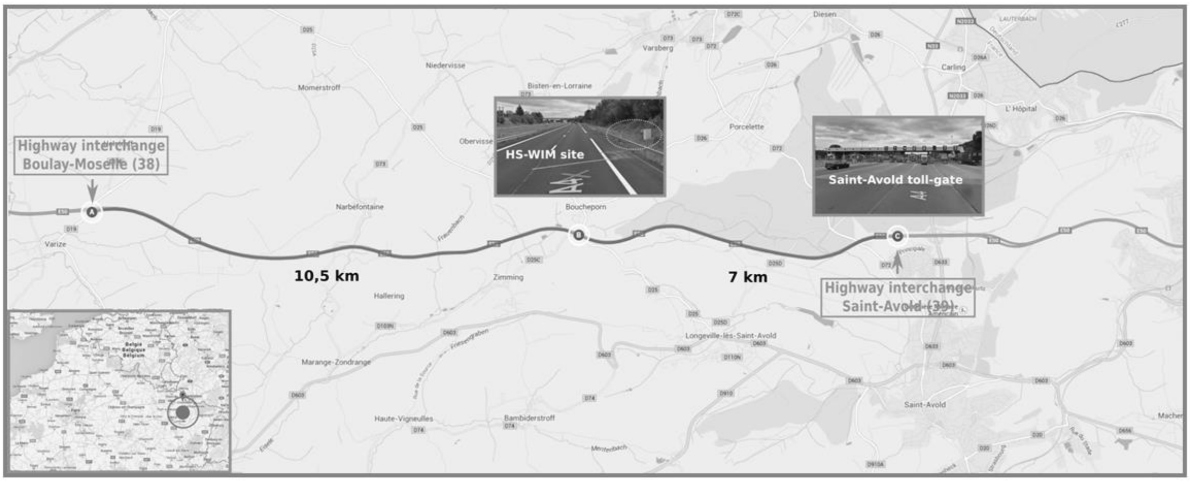


Figure 2 – Overview of the road-test site

Figure 3 – Static weighing system and park

Figure 4 – Saint-Avold toll-gate

The two industrial partners, Sterela (France) and Kapsch TC (Austria), and IFSTTAR-Cerema deployed each on the tests site a system based on an array of piezo-electric sensors. All together, 12 WIM sensors are installed on the site, and may be used to investigate the performances of multiple sensor (MS-WIM) systems. Additional no weighing sensors have been also installed to measure other influencing factors. Overall, an array of 46 sensors is installed on the test site. These sensors can be distinguished on the figure 5 :

- 12 weighing piezo-quartz sensors,
- 10 inductive loops,
- 6 position sensors (in bias),
- 7 temperature sensors at various depths,
- 9 geophones and accelerometers.

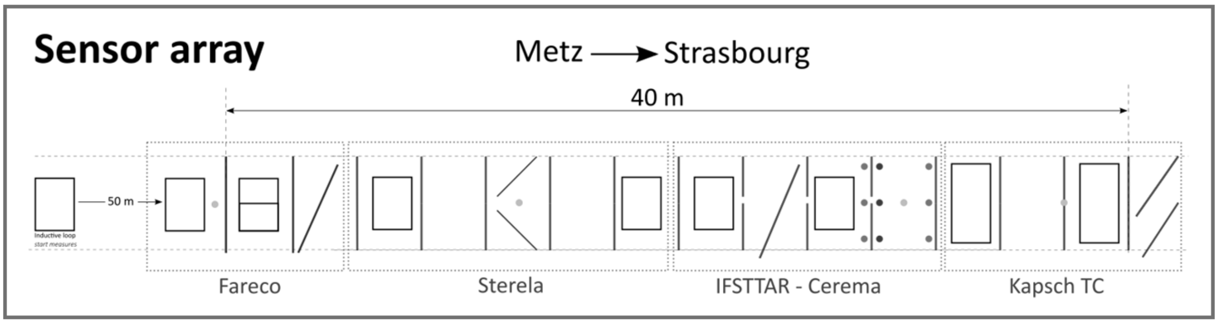


Figure 5 – Sensor array

3.1. Road and traffics characteristics

Despite the asphalt road was redone in July 2014, the site characteristics place it in upper limit of the class III COST323. The road has a straight line of 130 m upstream of the HS-WIM and 190 m downstream. The road has a longitudinal slope <2% and a cross slope <2.5% (usual cant). The road has a low rutting, between 2 and 3 mm. Deflections are also low, of the order of 20 to 50 1/100 mm. UNI of this road shows notes APL between 8 and 10 for a road portion of 1000 m centered on the HS-WIM. The daily traffic of all vehicles is 9632 vehicles in both directions, with 2093 vehicles over 3.5 tonnes, or nearly 22%. Overload rate is 1.3%, including

0.24% of more than 10%. This site was the only one which include a HS-WIM system, a static weight system and acceptable road characteristics for this experimentation.

4. Companies partnership and systems deployed

A call for participation have been launched inviting companies involved in WIM, including ISWIM members, to participate to the project, including laboratory tests, accelerated pavement testing facility test and on road trials. STERELA (France) and KAPSCH (Austria) joined the project as early as mid-2014 and proposed piezo-quartz sensors to three types of trials. TDC (UK) and Intercomp (USA) have also expressed an interest, above all for the road test, the first company with piezo-polymer sensors and the second company with its own sensor.

Companies marketing mature enough products and technologies to be assessed, and improved if needed, to meet the requirements of the direct enforcement are eligible as project partners. In this case they provide the hardware, software and knowledge required for studies and research related to the tests. Each company installs, calibrates and maintains its devices for the duration of the trial, complying with the specifications of the road site operator and the project managers. It provides to IFSTTAR and Cerema all measurements produced by its device (raw and elaborated) during all measures periods and shall communicate all information useful for the implementation of these 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 or low-speed weighing reference will be provided to partners for all vehicles weighed by their system.

IFSTTAR and Cerema will give a feedback to each partner with regard to their own system. They could support improving their systems for the purpose of direct enforcement. The partners undertake to carry out 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.

4.1 STERELA WIM system presentation

The WIM system installed in the trial site by STERELA is a multi-sensor grid to evaluate many types of configuration in order to find the best one according to the cost/accuracy ratio. The system is composed of 2 electromagnetic loops, 8 piezo-quartz sensors forming 4 lanes for weighing, 2 piezo-polymer sensors in V-shape to detect the position of the vehicle, and an ANPR camera for reading license plate of vehicles.

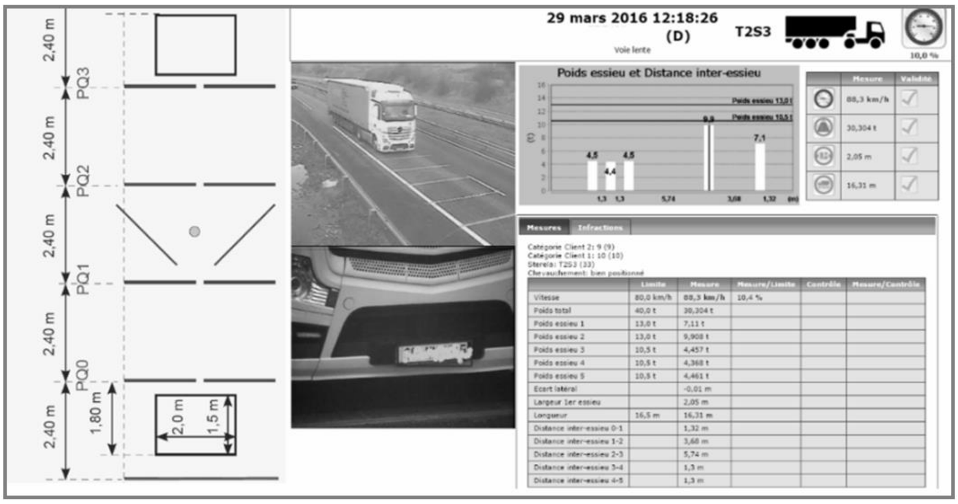


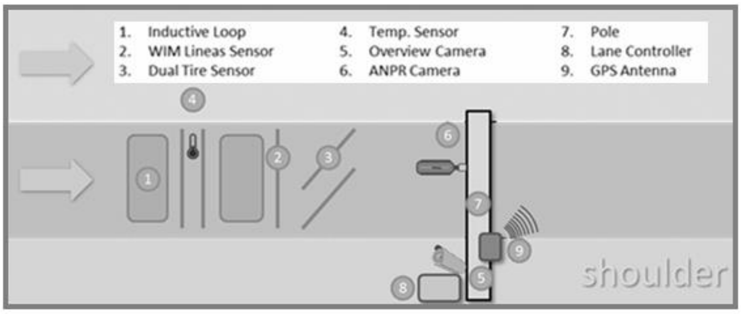
Figure 6 – STERELA "Global WIM" system

The system can provide in real time the data of weight from only 2 piezo-quartz sensors. At the same time, it records the output signals of each sensors, which are post-processed using a multi-sensor processing algorithm.

4.2 KAPSCH WIM system presentation

The WIM installation in France consists of High Speed Weigh-in-Motion components, which are installed along the road, in defined positions, to monitor vehicle parameters like speed, length, gross weight, axle weight, axle group weight, vehicle class. The system is composed by several components some of them are mandatory but others could be added, to provide additional data and functionality. The WIM Controller component will receive signals from components present in the road. The data is translated into useful data, like vehicle parameters – 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.

So the WIM pilot configuration in France consists of the following layout:



1. Inductive Loop
2. WIM Lineas Sensor
3. Dual Tire Sensor
4. Temp. Sensor
5. Overview Camera
6. ANPR Camera
7. Pole
8. Lane Controller
9. GPS Antenna

Figure 7 – KAPSCH WIM system

The WIM controller is also able to read other signals not related with vehicles, like GPS time and temperatures interior and exterior, for example sensors placed in the pavement. All this data will be collected, analysed and stored internally.

The KAPSCH Weigh-In-Motion System provides a unique validity check functionality. Due to driving behaviour or defects on vehicles passages are marked as non-valid measurements. The Validity Check System enables Direct Enforcement by showing 0 Validity flags, this means that the measurement is 100% valid and ready for Direct Enforcement.

5. Experimentation outlines

5.1 Main objectives

The test data will be used to validate sorting and filtering criteria and algorithms, allowing HS-WIM systems to provide a subpopulation weighed within the 5% tolerance required for direct enforcement. More than 30 periods of measures, each of one day, are carried out to end of 2015 to 2018 on HS-WIM sites and on the static weighing control area. Cerema organizes and manages these periods of measures and collect measurements from all systems ; the selected trucks are stopped by the police for weighing on static scales by the officers of the regional DOT (Lorraine). The data are processed by Cerema and IFSTTAR.

5.2 Installation, settings and calibration

Each company take in charge the installation, configuration, calibration and maintenance of its own equipment for the duration of the tests, respecting an installation diagram validated by IFSTTAR and Cerema. It supports related logistics, with the exception of traffic guidance equipment required to be borne by SANEF. The Cerema provides test trucks needed for calibrating all systems. Calibration and verification phase take place during four days after the various systems installations.

5.3 Tests plan

The test plans and accuracy or reliability assessment are based on the European Specifications of WIM (COST323) and on the requirements of the recommendation of the International Organization of Legal Metrology for weighing road vehicles in motion (OIML R134-1). Measurements are carried out in repeatability and limited reproducibility condition using rented test vehicles of different silhouettes and loads, and in full reproducibility conditions with vehicles from the traffic flow. The raw signals of all sensors are gathered and stored for further in-depth analysis and comparison with the IFSTTAR fatigue carousel dataset. More than 100 static weighing during each day are gathered to be compared with the dynamics weighing provided by WIM systems. Additional measures are collected such as the lateral position of the trucks, the pavement strains, vibrations, and temperature, and licence plates numbers for vehicles identification. The first three days of measurements in 2015 were devoted to calibrate and tune the various systems in order to start the experimentation at the 2016 spring. Up to seven known test trucks (C2, C3 and T2S3) were rented and have made every 8 passages on the sensors. Test trucks will be equipped with air suspension for driving axles and groups of axles. Several test plans were implemented by varying several criteria (speed, lateral position in the lane and load – median and full).

Several measurement campaigns have been already carried out using standard vehicles and in-flow vehicles under different traffic repeatable then reproducible conditions. One of the main stakes is to identify among all the dynamic measures, a subpopulation for which the accuracy of the measures of gross weights is lower than ±5% relative to the static reference weighing, and the one of the measures of single axle and axle of group is lower than ±8%. To identify with success these subpopulations requires to finely describe the measures, to detect in real time outliers and measures out of the tolerances.

Each daily campaign allows storing the raw signals provided by all sensors installed on the site and about 50 static weighing during each day which can be compared with the dynamic weighty measures processed by all the WIM systems, are done. In a first step, several campaigns were led in 2015 in order to calibrate all the systems. Up to now, 30 daily campaigns were conducted to store data. Finally, almost 1400 measures were acquired and these show really hopeful results. For example, in terms of trucks gross weights accuracy, the mean relative errors between dynamic and static weights is less than ±3% for the both systems.

Both systems are able to classify vehicles exactly according to their magnetic length, their number of axles and the distance measurements between them. The manufacturers' processing algorithms used to estimate static weights are their property and thus unknown to IFSTTAR-Cerema, so we do not know if these ones use that classification to calculate weights or not.

In its operational implementation, the direct enforcement system will use the license plate recognition by ANPR to identify vehicle and therefrom all the legal weight limits will be known using several vehicles identification systems (VIS) databases. Thus, the number plate with its corresponding dynamic weight measurements will allow to know if the vehicle is overloaded and has to be fined. Reflections will start on this in the coming months.

In contrast, it may be appropriate to take different accuracy classes depending on the vehicle classification or its gross weight. In fact, the higher the gross weight, the lower the relative error, which is the criteria required by the R134-1 recommendation. For example, it could be considered to take an accuracy of 5% for trucks weighing more than 19t and 10% for light-duty vehicles.

6. Main results

6.1 Accuracy and performance assessment

Two types of evaluation will be carried out on the data collected :

- conventional assessment of the accuracy class COST323 according to the principles of these specifications (statistical approach),
- assessment for the direct enforcement according to the OIML R134-1 class 5E accuracy.

The direct enforcement assessment involves checking that the systems, which integrates correction algorithms and sort criteria, produced two kind of vehicles subpopulations, all vehicles being weighed within tolerances OIML Class 5E or COST323 A(5). The first one subpopulation comprises all sorted and weighed vehicles (weighed within tolerances), the second one is limited to those of these vehicles having at least one overload (to single axle, group of axles or gross weight (GW)). All results presented in this article for STERELA and KAPSCH within under COST323 and direct enforcement assessments.

6.2 STERELA main results

The measures have been produced by STERELA from four lines of two piezo-quartz half-sensors processed from a computer model in deferred time.

As shown in figure 8, for the nine last road tests days, the COST323 accuracy class A(5) was obtained for traffic trucks for all kind of measurement.

The following results are those obtained since the last system recalibration on May 18th 2017 :

Conditions (1)	Test plan		Env^t	May, 18th 2017 up to September, 11th 2018 (9 daily campaigns)										
	R4		III											
SYSTEM	**Number**	**Identified**	**Mean**	**Std deviat**	**π_0**	**Class**	**δ**	**δ_{min}**	**δ_c**	**class**	**π**	**π**	**π'**	**Accepted**
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	(%)	(%)	**class**
gross weight	236	100,0	0,55	1,98	90,9	**A(5)**	5	3,7	3,7	5	90,9	97,9		**A(5)**
group of axles	240	100,0	1,60	2,81	90,9	**A(5)**	7,1	5,8	4,1	5	90,9	96,5	96,5	
single axle	462	100,0	-0,78	3,44	91,6	**A(5)**	8	6,4	3,9	5	91,6	97,0	96,9	
axle of group	683	100,0	1,63	3,76	91,9	**A(5)**	10	7,4	3,7	5	91,9	98,3	95,9	

Figure 8 – COST323 results for STERELA system

The following figure 9 shows the number of outliers relative to the OIML R134-1 accuracy class 5E on the same period :

System entity	Class 5E requirements	Number	Outliers	
gross weight	±5%	236	5	2.12%
group of axles	±8%	240	3	1.25%
single axle	±8%	462	9	1.95%

Figure 9 – OIML R134-1 results for STERELA system

6.3 KAPSCH main results

The measures have been processed in real time by KAPSCH from three lines of two piezo-quartz half-sensors.

Conditions [(1)]	Test plan		Env[t]	September 6th 2016 up to September, 11th 2018 (14 daily campaigns)												
	R4		III													
SYSTEM	Number	Identified	Mean	Std deviat	π_0	Class	δ	δ_{min}	δ_c	class	π	π	π'	Accepted		
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	(%)	(%)	class		
gross weight	522	100,0	1,76	1,87	91,7	A(5)	5	4,5	4,5	5	91,7	95,0				
group of axles	531	100,0	2,48	2,44	91,7	A(5)	7	6,1	4,2	5	91,7	96,6	96,5	A(5)		
single axle	1031	100,0	0,88	2,79	92,1	A(5)	8	5,3	3,2	5	92,1	99,3	96,9			
axle of group	1534	100,0	2,54	3,71	92,3	A(5)	10	8,1	4,0	5	92,3	97,4	95,9			

Figure 10 – COST323 results for KAPSCH system

As shown in figure 10, for the fourteen road tests days since recalibration, the COST323 accuracy class A(5) was obtained for traffic trucks for all kind of measurement.

The following figure 11 shows the number of outliers relative to the OIML R134-1 accuracy class 5E on the same period :

System entity	Class 5E requirements	Number	Outliers	
gross weight	±5%	522	18	3.45%
group of axles	±8%	531	5	0.94%
single axle	±8%	1031	16	1.55%

Figure 11 – OIML R134-1 results for KAPSCH system

7. Summary and conclusions

The 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. Road tests allow in this way to validate progress and to capitalize behaviour knowledges of the evaluated systems. The measures collected during the road trials phase and in real conditions, show very promising results, for these two kind of systems and confirm the proper installation of the various systems evaluated.

The project team is very confident about demonstrating the feasibility of achieving the requirements for a direct enforcement in France shortly.

The second phase of the project will prepare both the model approval and the certification procedure. In this way, we will discuss the various criteria that define the maximum permitted errors by type of vehicle (truck or light commercial vehicle), with the French legal metrology, the Ministry in charge of transports and the Interior Ministry which requires to not falsely fine more than 1% of the detected overloads.

8. Acknowledgements

Authors express their thanks to the DGITM (General Directorate for Infrastructure, Transports and Sea) of the French Ministry of Environment, Energy and Sea, for supporting this project, to the road operator (SANEF) and to the DREAL traffic officers for installing and operating WIM systems and performing controls. Special thank also for the industrial partners, STERELA and KAPSCH TC.

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Session 5 : WIM innovative Technologies

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WIM WITHOUT SCALES

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Abstract

In this paper, we consider a moving vehicle’s mass (WIM) measuring method using devices located inside the vehicle. The method is based on measuring the acceleration $\ddot{\mathbf{x}}$ and the propulsion force **F** when a driver accelerates the car, so that the mass **m** could be calculated according to Newton's second law as $\mathbf{m = F/\ddot{x}}$. The methods of obtaining the initial values (**F** and $\ddot{\mathbf{x}}$) and eliminating the interfering factors, such as friction, vibration and others are analyzed. The expected accuracy of the moving vehicle’s mass measuring is few percent, which should be acceptable for dynamic measurements of the excess load of a truck.

Keywords: Vehicle, Truck, Mass, Weight, Scales, WIM.

Zusammenfassung

Dieser Artikel diskutiert eines der Verfahren zur Messung der Masse eines sich bewegenden Fahrzeugs (WIM) durch darin befindliche Vorrichtungen. Der Weg ist, dass der Fahrer das Auto beschleunigt, und die Beschleunigung $\ddot{x}$ und die Antriebskraft F gemessen werden. Die Masse m des Autos wird gemäß dem zweiten Newton'schen Gesetz unter Verwendung der Formel $m = F / \ddot{x}$ berechnet. Es werden Wege betrachtet, um Anfangsdaten (F und $\ddot{x}$) zu erhalten und Störfaktoren wie Reibung, Vibration und andere zu eliminieren. Die erwartete Genauigkeit der Massenmessung des sich bewegenden Fahrzeugs beträgt wenige Prozent, was für dynamische Messungen der Überlast eines Autos als akzeptabel angesehen werden kann.

Stichwort: Fahrzeug, Masse, Gewicht, Gewicht, Waage, WIM.

1. Introduction

At present, the measurement of the mass of transport without its stopping (WIM) becomes more urgent, as it is shown in publications: INTERCOMP (2015); METTLER TOLEDO (2012); The Minebea Intec Axle Weighing Systems (2018); Belitsky G. et al (2016) and others publications. However, the placement of high-speed scales on the road is associated with a number of technical and economic problems. Furthermore, if overload is detected, the truck is sent to stationary scales, which is a complex and expensive device and usually is not located close to the WIM scales. As shown in WIM Society, (2018), there are known different ways to measure the weight of a transport with the help of devices installed on board. For example, it is proposed to install a load cell in a truck on each of its axles. However, this design is not widely distributed, probably, because of technical and economic problems. It is also possible to measure the load on each axle of the car by measuring the pressure in the air suspension (air springs). Yet not all vehicles are equipped with air springs; these are mostly heavy trucks manufactured, in recent years.

The device considered in this article can be used in trucks, truck tractors, agricultural machinery and other vehicles. The method considered here is not complicated and the used devices are cheap and are mass-produced by industry. The expected accuracy is few percent, which can be considered acceptable for dynamic measurements of the overloaded trucks, as shown by Bernard Jacob (2002) as well as Vdovin V. (2016).

In the described method, the weighing of a vehicle is based upon a well-known property of the matter the gravitational and inertial masses of a body are equivalent. The body inertial mass measured expressed in kg in the International System of Units is equal to the body weight measured on the Earth surface and expressed in kg in the Technical System of Units.

2. Methods of Measurement, Calculation and Design

2.1 Method of Measurement

The driver chooses a flat section of the road 200-300 meters long and implements a recommended driving mode on it, as shown in Figure 1. At first, he travels at a small constant speed $\mathbf{V_1}$. Then the driver accelerates the vehicle, trying to keep the constant acceleration $\ddot{x}_2$. After reaching speed V_3, the driver reduces the gas and rides for a while at this constant speed. In these three sections (1 - 3) the thrust force **F**, velocity **V** and acceleration $\mathbf{\ddot{x}}$ are measured.

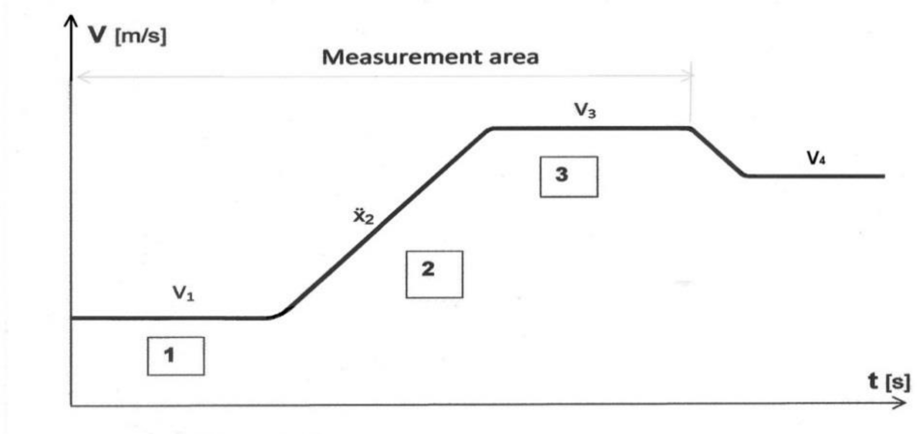

Figure 1 - Graph of the Speed

2.2 Calculation

The calculation of the vehicle's mass is performed. These mathematical operations are not complicated, and of course, they are made not by the driver, but by the simple processor, installed in the vehicle. The price of processor is few dollars.

If the vehicle moves at a constant speed, as shown in the first section, then, according to Newton's 1-st law, the sum of the forces acting on it is zero

$$F_{e1} - F_{fr1} - F_{a1} = 0 \quad (1).$$

Here are the forces acting in direction of the movement of the vehicle:
F_{fr} - the friction force of the vehicle on the road, and friction in transmission, N;
F_a - the force of aerodynamic resistance of air, N;
F_e - propulsion force (force that moves the vehicle), N.

In the second section, where the velocity increases with the acceleration $\ddot{x}_2$ [m/s^2], we can write according to Newton's second law

$$F_{e2} - F_{fr2} - F_{a2} = m\,\ddot{x}_2 \quad (2).$$

In the third section, where the velocity is also constant, an expression analogous to formula (1) is valid

$$F_{e3} - F_{fr3} - F_{a3} = 0 \quad (3).$$

The frictional force $\mathbf{F_{fr}}$ in all those equations is practically the same, since this is the force of dry friction and according to Hooke's law, it does not depend on the speed or changes a little. The aerodynamic resistance F_a varies significantly, since it depends on the speed of motion relative to the air. We use average resistance to the movement F_R, which corresponds to the middle of the section 2. It could be calculated from expressions (1) and (3) as an arithmetic average

$$F_R = 0.5(F_{e3} + F_{e1}) \quad (4).$$

From (2) and (4) we obtain the mass **m** [kg] of a vehicle with a load

$$m = [F_{e2} - 0.5(F_{e3} + F_{e1})] / \ddot{x}_2 \quad (5).$$

Other traffic options are also possible on the measuring section of the road.

2.3 Experiments and Design

Let us show how to measure the quantities in the equation (5). The acceleration $\ddot{x}$ can be determined by differentiating the output signal V of the speedometer. Graphs for V and $\ddot{x}$ obtained in an experiment, are shown in figure 2 below. However, this method of measuring acceleration has several drawbacks. First, not all vehicles have an output as an electrical signal from the speedometer (tachograph). Second, those devices (speedometer or tachograph) have a relatively high error, about 10 km/h. Third, when the experimentally obtained signal is differentiated, the error increases. Therefore, the error of acceleration obtained by this way can be 10% or even more. This is a bit too much for measuring the mass of a vehicle.

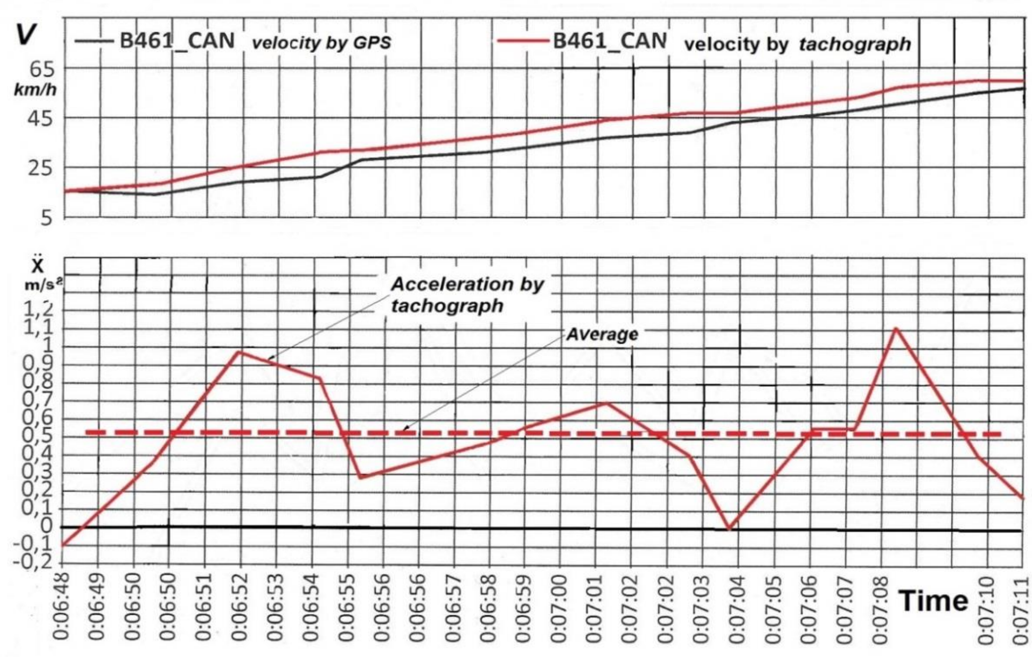

Figure 2 - Results of the Experiment on Measuring Speed and Acceleration of a Truck.

To increase the accuracy of the acceleration measurement, it is useful to install an accelerometer in the vehicle. From a wide variety of accelerometers manufactured by the industry, one can choose a device that is suitable for the task according to the requirements:

a) The measuring range should be approximately ± 2g (g ≈ 10m/s^2). In case of non-accidental acceleration or deceleration of a heavy truck, the acceleration does not exceed these limits.
b) The eigen frequency of the accelerometer should be at least 1000 Hz, since it must be higher than the upper frequencies of the input signal. High frequencies can strongly excite the accelerometer's oscillations at its resonance, which will lead to significant measurement errors. Parts of the vehicle and parts of the load may well vibrate at frequencies of several hundred hertz. High frequency oscillations also come from the tread of the rotating wheels and the running engine.
c) It is desirable to use an accelerometer that is operable not only in dynamics, but also in static. The sensitivity of such an accelerometer is easy to verify without any complicated adaptations such as vibrating bench. To do this, simply rotate such an accelerometer by 90^0, so that the direction of its sensitivity axis changes from horizontal to vertical. The input signal will change to 1g.

Based on these requirements, we may choose, for example, the accelerometer ADXL-103 . Its main characteristics: Operating range ± 1.7g; Resolution 1mg; The eigen frequency is about 10KHz; Precision is about 1%. The price of the accelerometer is $12. (Analog Devices, 2010).

The electronic circuit of the accelerometer should have a high-pass filter. The lower frequency limit for the filter should not exceeds a few hertz, since along with above mentioned high-frequency oscillations there are also quite low-frequency oscillations. They could be caused, for example, by poorly fixed load, or by coupling with a trailer, from splashing a liquid in an unfilled tank, and others. All these oscillations are interference that must be eliminated by this electric filter.

Let us now consider the methods for driving force's measuring. Most modern trucks have engine monitoring systems installed. Some of these systems have an engine power meter, as shown in figure 3. Part of the power is lost in the transmission and is spent for auxiliary needs, but most part kP [W] of it is given to the wheels and creates a driving force for F_e [N]

$$F_e = kP/V \qquad (6).$$

Here: P - power of engine, W;
k - the engine power factor to use;
V – speed of vehicle, m/s;
F_e - driving force for, N.

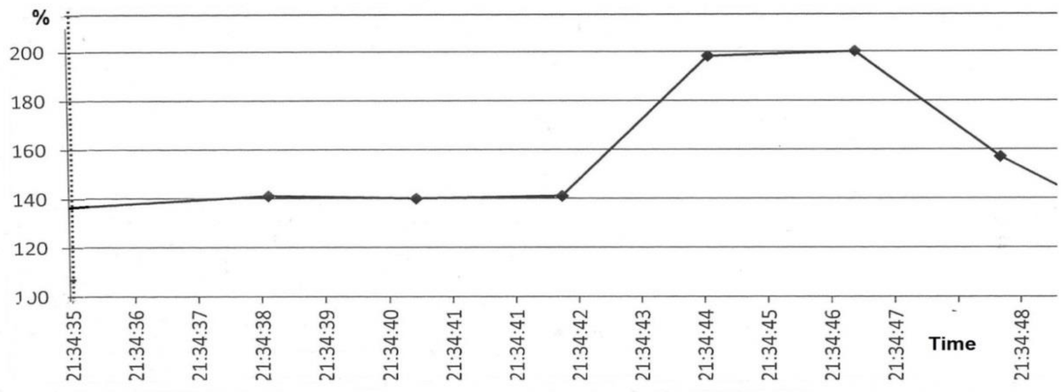

Figure 3 - Results of the Eexperiment to Measure Power of Engine.

It is difficult to calculate the coefficient **k**, it is easier to determine it experimentally. To do this, with a technical check, one must weigh the vehicle on a stationary scale, and then determine its mass in the manner described above. According to formulas (5) and (6), we obtain **k**, as the ratio of the masses obtained at these measurements. To do this, during a technical check, one must measure on a stationary scale the weight of the vehicle m_1, and then determine its mass m_2 as was shown above. According to formulas (5) and (6), we calculate **k**, as the ratio of the masses obtained at these measurements as

$$k=m_1/m_2 \qquad (7).$$

Some vehicles have a measuring system that can display the amount of torque **M** [Nm] on the engine crankshaft. Using the rotational speed **ω** [rad/s] of the crankshaft, we learn engine power **P** [W]

$$P = M\,\omega \qquad (8).$$

Next, we perform the calculations in the same way as shown above when using the power measurement.

The error of the indicated power and torque meters is approximately 5%. Therefore, the error in measuring the mass of the vehicle will not be less than the specified value.

If the engine of the vehicle does not have any electronic measuring system at all, then it is possible to determine the torque by the known method of the "Engine - scales". With this method, it is necessary to measure the reaction forces of engine supports. Usually the engine is placed on 3 pillars, called pillows. Under these pillows, it is possible to put load cells. The torque is obtained from the system of 6 linear equations of equilibrium. In most cases, only one equation is necessary.

$$F_1L_1 + F_2L_2 + F_3L_3 - GL_G - M = 0 \tag{9}$$

Where: F_1; F_2; F_3 – vertical reaction forces of engine supports, N;
G - weight of engine, N;
L_1 ; L_2 ; L_3 ; L_G - shoulders of forces, m;
M - torque of engine, Nm.

It is convenient to use, for example, load cell CWFS-100 of the company "Bonshin ". The error of these sensors is less than 0.5%, the range is 1000 N, the price of one sensor is $330, and the price of one indicator is $320, (BONGSHIN, 2018). The error of measurement of the shoulder Li of operating forces is about 1%. It can be expected that the error in measuring the engine's torque by the method will not exceed 1.2%. Other load cells, which are less accurate but cheaper, can also be used.

2.4 Measurement Error

As it follows from expressions (5.7 and 8), the mass m of the vehicle is a product of five entities, i.e.

$$m \sim kM\omega \left(\frac{1}{V}\right)\left(\frac{1}{\ddot{x}}\right) \qquad (10),$$

where $\ddot{x}$ is vehicle acceleration, M is engine torque, ω is rotation speed of the output shaft of the engine, k is engine power utilization factor, and V is vehicle speed. Let now μ_i and σ_i denote, respectively, the true value and the standard deviation of the i-th entity. It is easy to see that the standard deviation σ_m of the calculating of mass through the above formula obeys the following equation (Novitsky P. and Zorgaf I., 1991)

$$m^2\sigma_m^2 = \sum a_1^2a_2^2a_3^2a_4^2a_5^2 \qquad (11),$$

where the sum is taken over all products in which each a is either μ or σ, but at least one of the five a's is σ. There are 31 members in this sum. However, the members that contain two or more σ's have a small contribution to the whole value of the sum. The main contribution is given by

$$\mu_1^2\mu_2^2\mu_3^2\mu_4^2\sigma_5^2 + \mu_1^2\mu_2^2\mu_3^2\sigma_4^2\mu_5^2 + \mu_1^2\mu_2^2\sigma_3^2\mu_4^2\mu_5^2 + \mu_1^2\sigma_2^2\mu_3^2\mu_4^2\mu_5^2 + \sigma_1^2\mu_2^2\mu_3^2\mu_4^2\mu_5^2 \qquad (12).$$

Plugging in the values of μ's and σ's, we get $\sigma_m = 0.063 = 6.3\%$. This corresponds to the accuracy class B + (7) of COST323 for WIM as it is shown in Bernard Jacob (2002). The largest error is obtained when measuring the velocity, it is $\sigma_5 \approx 0.05$. It gives most of the error value. If we do not limit ourselves to the speedometer (tachometer) passport dates, and perform its additional calibration, we can get lower error of mass measurement $\sigma_m \leq 5\%$, that is fit into accuracy class A(5), according to COST323.

3. The Next Stage of the Work

To test the suitability of the described method, it is necessary first of all to certify the installed devices. Also, it is necessary to carry out additional tests of several trucks, empty and loaded.

It is advisable to use trucks of various types and different types of cargo. It is necessary to collect a sufficient number of measurement results to determine the accuracy and reliability of the described system for measuring weight. Such studies can only be conducted in conjunction with the ISWIM community and with the participation of a specialized vehicle company.

4. Conclusions

1. A method and apparatus for moving vehicle's mass measuring using a measuring devices built into it are described.
2. Measurement is made when driving without stopping the vehicle - WIM.
3. The system does not require the use of external scales.
4. The expected error in measuring the mass (weight) does not exceed a few percent, which can be considered acceptable for WIM systems.

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LEARNINGS FROM ON-BOARD MASS TYPE APPROVALS

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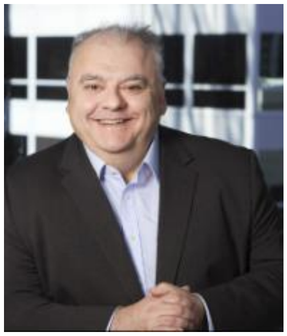

Obtained B.Sc. from Sydney University, Australia has worked in transport strategy and policy, and central agencies for over 20 years. Has worked with TCA in strategy and policy advice on new applications and technologies since 2013.

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Abstract

Transport Certification Australia has developed a type-approval process and supporting systems for assessment of on-board mass (OBM) monitoring and reporting systems. Australian road managers have long sought timelier, on-road data relating to the dynamic mass of vehicles using the road network. TCA's type approval process assesses both organizational capability of OBM suppliers for the market (including probity and financial assessment components) and functional and technical capabilities of the OBM systems and their components. Learnings from this process include the need for assessing organisations to take a flexible and performance-based approach, ensuring the broad needs of the market and end users is accommodated within the framework, and that the framework supports the development of new use cases for the technology and integrates within existing technology and telematics frameworks.

Keywords: Heavy Vehicles, Freight transport, Weigh-in-Motion, WIM, On-board mass, OBM, Transport Certification Australia, TCA.

Résumé

Transport Certification Australia a mis au point une procédure d'homologation, et des systèmes auxiliaires pour évaluer les systèmes de pesage et de compte-rendu automatiques pour le pesage embarqué (OBM). Les gestionnaires de routes australiens recherchent depuis longtemps des données plus précises sur la masse dynamique des véhicules empruntant le réseau routier. Le processus d'homologation de TCA évalue à la fois les capacités organisationnelles des fournisseurs d'OBM pour le marché (y compris évaluation de probité et financière), et les capacités fonctionnelles et techniques des systèmes OBM et de leurs composants. Les enseignements tirés de ce processus incluent notamment la nécessité d'évaluer les organisations selon une approche flexible et basée sur les performances, en veillant à ce que les besoins généraux du marché et des utilisateurs finaux soient pris en compte, et en garantissant que le cadre prend en charge le développement de nouveaux cas d'utilisation de la technologie. et s'intègre aux cadres technologiques et télématiques existants.

Mots-clés: Poids lourds, frêt, pesage en marche, WIM, pesage embarqué, OBM, Organisme de certification australien, TCA.

1. Introduction

Transport Certification Australia (TCA) is the Australian government body responsible for providing advice, accreditation and administration services for public purpose initiatives involving the use of telematics and related intelligent technologies.

TCA performs a critical role in supporting the adoption of telematics and related intelligent technologies in accordance with the National Telematics Framework (NTF), limiting the risk that government bodies pursue initiatives which may:

- Delay progress
- Create duplication
- Multiply costs
- Contribute to a fragmented approach to telematics and related intelligent technologies.

TCA's active management of an open technology market - which focuses on outcomes rather than technology prescription - is central to our purpose, and the delivery of our purpose.

At the request of Australian governments and industry, TCA developed a program for On-Board Mass (OBM) measurement within the NTF. Commencing in 2008-09 with an assessment of the performance of OBM systems (TCA, 2009), this progressed into the development and testing of functional and technical specifications for OBM systems. Commercial OBM systems commenced in 2013, as part of the Interim-OBM Solution administered by TCA.

In October 2016, an operational learnings report was published, and made available to Australia's road and transport agencies (Koniditsiotis and Hill, 2018).

TCA has now developed a functional and technical specification and type-approval process for entities seeking to bring certified OBM monitoring and reporting systems to market. Private providers have now sought assessment under this framework, and TCA has significant further learnings from this process.

2. Importance of measuring vehicle mass

2.1 To road managers and government

Vehicle mass (both static mass and real-time mass, while the vehicle is in motion) are critical parameters for the design, construction, management, operation and maintenance of our road networks. Road agencies globally have significant interest in timelier on-road data relating to the mass of vehicles using the road network and real-time, on-board mass measurement has long been an ideal for managing the risks of restricted access vehicles to vulnerable assets.

Vehicle mass measurement is important for a variety of reasons including:

- Compliance with statutory obligations for operation within the road network, including both axle group and gross vehicle mass tolerances. There are existing schemes which allow vehicles to operate on the road network where obligations are placed on operators to be aware and manage vehicle loading. OBM systems have been recognized as one potential method of demonstrating compliance in Australia, allowing vehicles enhanced access to the road network. This is already underway, with OBM systems being used as part of the Queensland and New South Wales interim OBM solution. This scheme allows vehicles expanded access to the road network, including bridges, because of the enhanced knowledge of the axle and gross vehicle mass of a vehicle.

- Monitoring performance of contractors. Local government contracts for the collection of waste are increasingly being monitored for mass for assurance that the waste disposal vehicle is within tolerances. Local councils also want to know the mass that is collected for trade and service monitoring purposes.
- Monitoring environmental risks. Environmental regulators have become interested in monitoring the movement of both solid and liquid waste and its disposal at designated areas.
- Compliance with other regulatory regimes. The Australian Maritime Safety Authority (AMSA, 2016) is responsible for oversight of the mass of container movements in and out of ports in Australia and is working with TCA to assess Type-Approved OBM systems as a potential method of meeting container and other load weighing requirements.

OBM systems are increasingly being considered as a means of smarter regulation in which red tape is being removed and providing greater confidence to both regulators and industry.

In addition to ensuring compliance with regulated mass and vehicle limits, governments are also keenly interested in vehicle mass data more strategically. This data is valuable to improve planning, management, operation and maintenance of roads for the use of heavy vehicles.

On-board mass measurement represents a paradigm shift from previous, largely roadside methods, such as weighbridges, portable scales, and high-speed weigh-in-motion systems. The nature of roadside equipment means that data is limited to specific points on the network. On-board mass measurement allows data to be collected for the entirety of journeys, including data that agencies are most interested in monitoring, including high mass vehicles or those operating in dense urban areas.

Because of this lack of vehicle-specific data, road managers in particular have been forced to include significant safety margins in the design of roads, and particularly vulnerable assets such as bridges and culverts. The primacy of protection of public safety, and assurance of the lifespan of public assets has meant that, in the absence of accurate vehicle-based data, that assets have not been able to be utilized to their full, safe capacity.

Australian structure standards for bridge assessment have recently been updated (AS 5100.7:2017) (SA, 2017). This revision incorporates the possibility to allow for increased flexibility and productivity for vehicles engaging in increased monitoring. The updated standard incorporates reduced traffic load factors for vehicles monitored through the Intelligent Access Program (IAP) and OBM for the Ultimate Limit State (ULS) (Koniditsiotis and Hill, 2018).

This is an important initiative because on-board mass monitoring is not simply being used for compliance and enforcement, rather to also recognize the conservative nature of infrastructure design and thus better ‘sweat the asset’.

2.2 To operators

Transport operators, consignors and others in the supply chain have an interest in the mass of vehicles.

Ultimately an operator and driver of a heavy vehicle needs to know the mass of their vehicles for several reasons. Including:

- Ensuring that ultimately it is paid for the mass that it is carting. If any component of the pay load is over or under mass, it may have direct consequences to the revenue that is generated.
- Ensuring that the vehicle is complaint with regulated limits, of both overall mass limits, but also distribution of loading across axle groups.
- Distribution of loading can significantly impact the way the vehicle operates from a wear and tear perspective, its maneuverability and hence safety. This has significant safety consequences
- Providing assurance to other commercial partners and customers in the supply chain that they are compliant with the law and managing public and employee safety.

3. Road safety implications of improved mass data

Australian data has demonstrated (Hassall and Thompson, 2016) that vehicles which operate under restricted access (including those operating under a condition of telematics monitoring) have significantly higher safety performance on roads than a control group of similar, unrestricted vehicles.

One of the reasons cited for the safety improvement, is that higher-productivity vehicles are subject to increased monitoring. Operators and fleet managers who have invested significant resources into the vehicles desire assurance for their investment, and road managers seek assurance that these heavy vehicles are compliant with route and mass conditions.

Another key reason for the improved safety profile of these higher productivity vehicles is precisely because of their productivity benefits. While not only offering the potential for increased returns to transport operators, these vehicles have the overall impact of reducing the number of freight trips needed to move any given volume of freight.

In 2016 Infrastructure Australia (IA) recognised that "…low-cost in-vehicle transponders and satellite tracking are increasingly being used to open up parts of Australia’s road network to suitably-specified trucks. Productivity improvements of up to 100 per cent are being realised, and associated reductions in fuel use are cutting emissions" (IA, 2016).

To unlock this latent productivity and allow heavier vehicles to access the network, road managers require assurance that certain types of higher productivity vehicles are not loaded over the acceptable safety limits for the road network for which access has been approved. Certified, real-time, in-vehicle mass measurement is one critical mechanism to access this data.

4. LEARNINGS

The 2016 TCA assessment (Koniditsiotis and Hill, 2018) identified several operational learnings which were incorporated into subsequent program development.

Since this time, TCA has further refined the OBM specification, and governance arrangements based on these and subsequent learnings (TCA, 2017b). In September 2017, TCA led a national workshop with road managers, technology providers, and freight operators to identify learnings and opportunities for the future. The key operational learnings identified are related to:

- Accuracy
- Calibration
- Roles and responsibilities.

4.1 Accuracy

As outlined in Žnidarič (2015), the accuracy of OBM systems relies upon a number of factors, including frequency and type of calibration, road surface quality and road roughness, and vehicle activity. The OBM Type approval process identified that key operational factors in particular which affected accuracy were the need to be on a level surface and with zero vertical acceleration.

The level of accuracy can also vary in a non-linear manner, depending on the mass of the vehicle (i.e. high accuracy may be achieved at certain mass, but lower levels of accuracy at other masses). For example, unladen vehicles were found to have lower levels of accuracy than fully laden vehicles (TCA, 2015).
A key requirement of the specification that has been developed is accuracy. Axle group mass measured by the Mass Sensor Unit (MSU) must not deviate from the absolute axle group mass by more than 2% of the maximum permissible mass (i.e. the legal mass limit for an axle group) of the axle group for 98% of observations.

4.2 Calibration

Periodic calibration is essential to ensure accuracy.

Claims by some OBM suppliers that systems are entirely 'self-calibrating' don't stand-up to scrutiny, however, some system may have lower need for period calibration depending on the design of the systems. Determining the period between calibrations is subject to several factors, including:

- The technology used, and its installation on a vehicle.
- Environmental factors.
- The number of recorded malfunctions and tampers.

The process of assessing OBM systems identified that systems retained reasonable levels of accuracy on average after 6 month calibrations (TCA, 2015). As illustrated in Figure 1 below, most results for the performance of systems six months after calibration fell within the 2% range of error (with some statistical outliers, indicating the need for closer attention and variation in calibration schedule). Systems did not necessarily follow a pattern of slow deterioration and loss of accuracy, but rather failed to operate satisfactorily resulting in significant errors. These failures appeared to result from events including software or OBM system malfunctions, tampering or other such events.

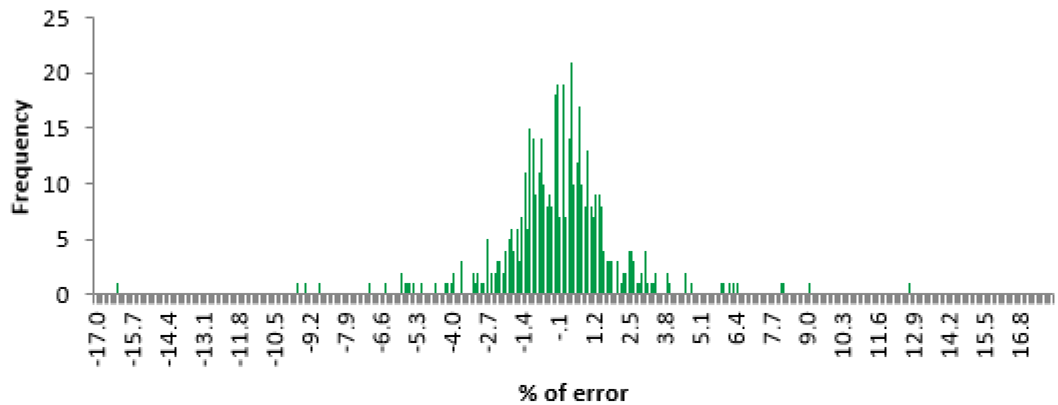

Figure 1: Error distribution graph for re-calibration records taken six months after initial calibration – full load (TCA, 2015).

At the 95% confidence level, these results showed that, on average, six months after initial calibration, the OBM System's accuracy meets the requirement of 2% and the measurement results are compliant with the accuracy requirements before the next calibration within 82.59% - 89.25% confidence interval.

The type-approval process of systems has detailed that the supplier must provide a suitable, quality system for calibration, based on many factors, rather than only time. As an example, some suppliers are constantly monitoring system performance and advising on calibration needs. Importantly this oversight also identifies likely malfunction or tampering.

4.3 Roles and responsibilities

The relationships between technology providers in a vehicle-based environment can be complex. For example, the suppliers of OBM System equipment are often different from those which provide telematics services.

Boundary and interface issues impact on the resolution of malfunctions and tampering (it can be difficult to determine if the problem is with the OBM System, or the telematics service). Clarity in the various roles and responsibilities have been addressed, as far as possible, within the OBM specification (TCA, 2017b).

5. Opportunities

In addition to learnings to improve the operation and function of the OBM program, TCA and its stakeholders have identified a range of potential opportunities (TCA, 2017a). Some of these opportunities (such as optimizing the mass limits for vulnerable assets) are already being realized. The key opportunities identified included:

- Improved regulator assessment capability.
- Improved on-road enforcement.
- Cross-verification between OBM and on-road weigh in motion systems.

- Establishing (based on existing frameworks) a standardised approach for the collection of vehicle mass and configuration data, and mechanisms for securely sharing data between relevant stakeholders.
- Optimised road asset utilisation and network planning.
- Supporting other applications or regulatory uses.

5.1 Improved assessment capability

An opportunity (and challenge) is the development of improved assessment capability that arises during the process of developing and assessing OBM performance criteria and applications from commercial system providers. The specification is performance-based in nature which maximises flexibility and adaptability of the framework and supports innovation.

The assessment of OBM System 'types' focuses on performance-based outcomes, rather than prescribing technological approaches. Innovation is encouraged in system applications, which requires assessment and testing to be similarly innovative.

Developing and maintaining the appropriate capability and systems to assess, advise on and support the marketplace for performance-based systems such as the OBM specification will remain a constant challenge. TCA has identified the need to remain technology agnostic, and open to a wide variety of ways to achieve the objective outlined in the specification.

5.2 Improved on-road enforcement

Until the development of certified OBM systems, compliance and enforcement of mass breaches was primarily undertaken only through dedicated, stationary facilities such as weighbridges or portable scales. High speed, weigh-in-motion measurement was primarily valuable for enforcement agencies as an information gathering tool and to filter for compliance and enforcement. The OBM program will allow for direct enforcement during the driving task, rather than requiring enforcement officers to use portable scales, or direct a vehicle to a weighbridge. The OBM non-conformance reporting arrangements provide road managers and regulators with the tools to address non-compliant behavior at the root cause and implement systemic solutions, rather than only ad-hoc enforcement.

5.3 Cross calibration and verification

The 2017 TCA WIM Forum identified several opportunities related to utilizing data from in-vehicle and on-road mass measurement systems for the purposes of cross-verification and identification of faults and malfunctions. The forum importantly recognised that on-road and in-vehicle monitoring are not in competition – they each monitor mass for difference purposes and policy uses.

Unlike static weighbridges and high-speed weigh-in-motion systems that provide a point in time somewhere on the road network measurement of mass, OBM systems can provide a continuous stream of data which better matches the day to day operations of a vehicle. This data combined with an increased level of integrity (as confidence and assurance in the quality of the data) provides a whole new set of opportunities to both industry and government in the way heavy vehicle operations take place.

This is an opportunity to cross validate with stationary equipment to demonstrate and test the accuracy and integrity from WIM on-road and in-vehicle systems, and allow for system optimisation, by comparing data readings. This could be particularly important when considering the timeframes for calibrations of systems – and allowing cross system validation could be complementary to extending the time between mandatory calibrations through conventional means.

5.4 Standardised and secure data collection, storage and sharing

Establishing a standardised approach to the collection of vehicle mass and configuration data, by building upon established practices (including the NTF Data Dictionary) was identified as a key opportunity and priority by stakeholders. Another opportunity was ensuring that data collected through these systems is protected by the appropriate safeguards and protections to enable the access and use of vehicle mass and configuration data in a secure and safe manner that provides confidence to stakeholders that data is not used for undisclosed or unintended purposes.

TCA currently operates within a strict and punitive privacy and data protection legislation framework (set out in Chapter 7, of the *Heavy Vehicle National Law 2012*) (Queensland Government 2012) which creates the opportunity for this data collections, storage, aggregation and sharing. This or equivalent governance arrangements may be a key component in reproducing similar capabilities.

5.5 Optimised road asset utilisation and network planning

Improved optimisation of the road network has already commenced with recent Austroads work that included an allowance in the bridge standards guide for a reduced road bridge safety factor if knowledge of mass is available through the use of high-assurance OBM systems. This is a recognition that existing pavement and bridge design and management theorems are conservative in so much as they make assumptions about the loading of vehicles in operation (Koniditsiotis 2017).

This has traditionally been an appropriate approach given there has been no quantitative information across the network. With the availability of the individual OBM systems in vehicles, there is an opportunity for the industry to negotiate unique access arrangements and unique operating environments where there is knowledge of the mass in a manner that regulators and road manager have never had.

If correctly adopted, certified OBM monitoring provides a huge opportunity for increased productivity (and improved safety and environmental outcomes) and micro economic reform for the industry, and for Australia without compromising safety.

Several case studies of where this has been implemented have been developed with road agencies and service providers to demonstrate the practical implementation of this opportunity.

5.5.1 A-Doubles transporting export produce - Queensland

Introduced in 2011, A-Double combinations were permitted by the Queensland Government to improve the efficient and productive transport of grain from rural locations to a major port for export. Conditions of use include Performance Based Standards (PBS) approval (permitting vehicles to operate up to 85 tonne Gross Vehicle Mass), monitored through the IAP for route and speed compliance (maximum of 100km/h), and fitted with OBM Systems.

The use of OBM Systems has enabled a reduction in bridge load factors on bridges along the 160km route when considering permitted routes for these vehicles. Without these reductions in load factors, these vehicles would not have been able to operate. The use of A-Double combinations has halved the number of vehicle movements that would otherwise be required to support the export market of grain produce.

5.5.2 Higher Productivity Freight Vehicles (HPFVs) – Victoria

Introduced in 2013, HPFVs were introduced under the Victorian Government's 'Moving More With Less' policy. HPFVs are longer than standard B-Double combinations and:

- Are approved as PBS vehicles (73t Quad-Tri and 77.5t Quad-Quad B-Doubles), up to 30m in length.
- Monitored through the IAP for route and speed compliance (maximum of 90km/h)
- Fitted with OBM Systems.

These vehicle combinations are able to operate on parts of the road network that were not previously available. The 'Moving More With Less' policy has put downward pressure on the number of trucks operating on Victorian roads by facilitating the use of more efficient vehicle combinations on approved roads.

5.5.3 Safety, Productivity and Environment and Construction Transport Scheme (SPECTS) – New South Wales

Introduced in 2016, SPECTS allows for 'general' (unrestricted) access to vehicles operating at Higher Mass Limit (HML) axle loads, which would otherwise be subject to restricted access. Transport operators are eligible to participate in SPECTS if vehicles are approved through the PBS scheme, monitored through the IAP for route compliance, and fitted with OBM Systems.

140 bridge restrictions in Sydney have been removed (only 1 bridge restriction remains) – based on the assurance available to road agencies by knowing the location and mass of vehicles. SPECTS was introduced with the aim of reducing the number of vehicle movements across Sydney, which has increased as a result of increased infrastructure investment and construction.

5.5.4 Description of two initial type approved OBM systems

Tramanco achieved type approval of the CHEK-WAY® Eliminator OBM system in August 2018. This system is multiplexing, allowing for more trailers to be 'plugged in', up to an eight (8) channel system. It also uses a unique software programme which also includes two functions called AUTO-ID® and AUTO-CAL® to monitor all vehicle connects, disconnects, their location as well as the type of combination as illustrated in Figure 2.

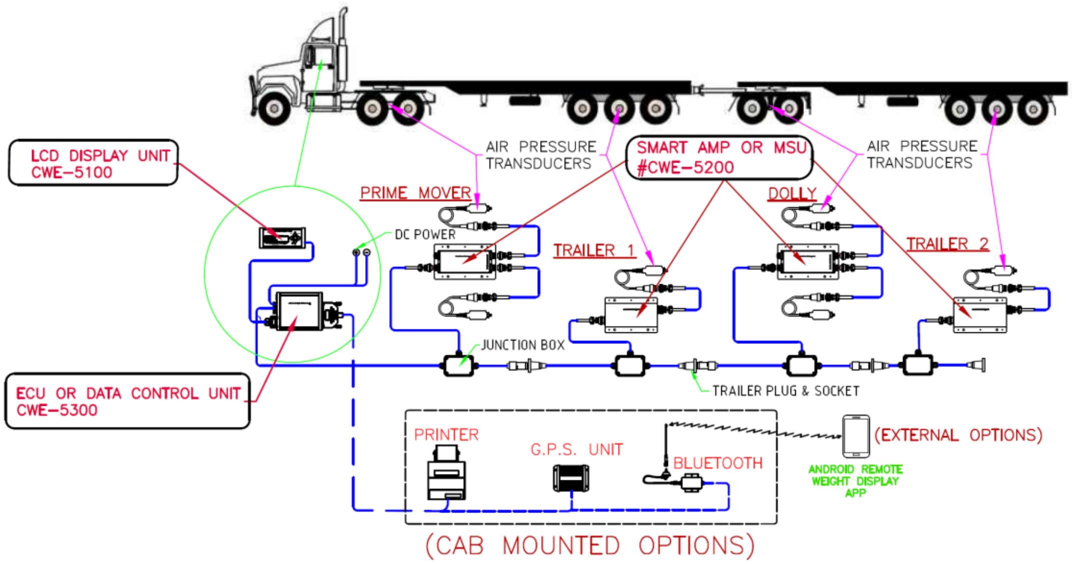

Figure 2: Chek-Way Type Approved OBM System – A-double installation.

Loadmass, trading as Loadman Australia also achieved type approval of its LM300 Can-Coder OBM System in August 2018. Can-Coder technology systems accept multiple trailer inputs from air suspension pressure transducers or load cell installations including mixed sensor applications. The system allows for trailer swapping and combination changes, and displays data locally in the cab or via Bluetooth for Android devices.

This system allows for continuous feedback and analysis of data, effectively allowing for data and system verification continuously in real time. Annual public weighbridge certification provides an external verification and calibration of the system. Additionally, the system allows for cross verification of static WIM sites through exchange of raw data.

6. Supporting other applications or regulatory uses

At present, on-board scales are relatively new technology, and like all new technologies, are likely to grow more cost effective and ubiquitous as the technology becomes more mainstream. As an example, many new heavy vehicles are fitted as standard with electronic braking systems and air-bag suspension systems that, when calibrated correctly, are capable of effectively measuring the mass of the vehicle in compliance with the OBM specification. As these technologies become more common across the vehicle fleet, the cost of OBM participation is likely to become more attractive - leveraging the productivity and safety benefits available and supporting broader monitoring applications.

The opportunity presents itself for the use of both on-road and in-vehicle weighing systems to provide greater confidence to all stakeholders and provide for increased productivity while also improving the safety of road users.

The OBM Program is a new functionality within the National Telematics Framework. The NTF provides the platform by which vehicle mass data collected by type-approved OBM Systems can support a diverse range of policy outcomes, regulators and industry sectors (see Figure 3).

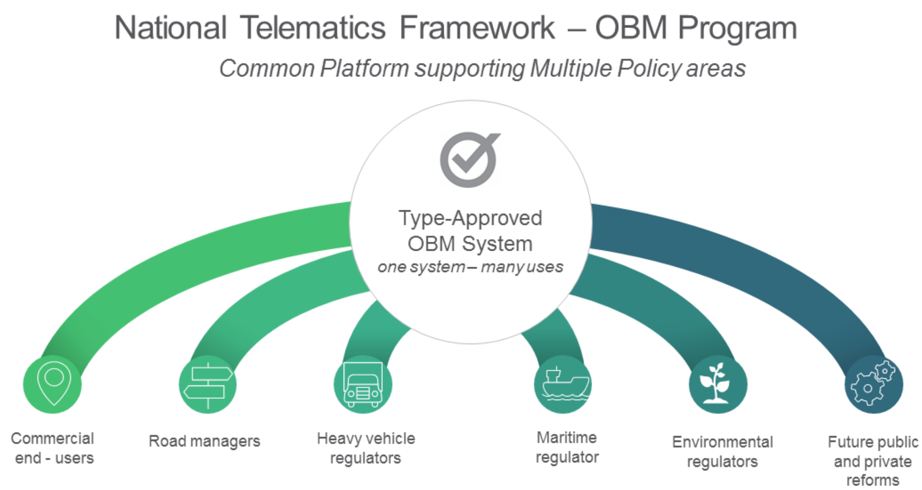

Figure 3: National Telematics Framework – A common platform supporting multiple policy areas.

There is significant potential for the OBM program to support other applications beyond the existing access conditions framework. These might include mass-distance-location (or even time-of-day) road user pricing for freight vehicles, dangerous goods monitoring, and leveraging the interoperability of being part of the NTF (including utilizing a common data dictionary, data platform and analytics methodologies).

Vehicle mass data may be incorporated with data from other applications of the NTF, including spatial, temporal and speed data available through the IAP, to enable vehicles to be assessed against the relevant operating conditions. By working within the NTF and leveraging off a common data dictionary and other features, applications such as the OBM program can be interoperable with other equipment and applications, and leverage data for multiple purposes and users.

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ASPHALT EMBEDDED FIBRE OPTIC WEIGH-IN-MOTION TECHNOLOGY

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Abstract

A fibre optic sensing technology based on Fibre Bragg Gratings (FBGs) and a high precision dynamic detection system is demonstrated for capturing high resolution deformation of the asphalt. Individual tire impacts on the road are recorded statically and dynamically, allowing to detect the wheel type, axle count, vehicle speed, position in lane, consequently wheel, axle and vehicle weight can be inferred at full highway speeds. Additionally, the system provides a unique set of results in capturing the asphalt deformations in-situ at the site, including the deformation imprint and waves of the viscoelastic material in unprecedented detail which allow for detailed analysis of asphalt models as well as maintenance prediction models. This level of detailed asphalt deformation enables a significant opportunity to monitor the asphalt , such that maintenance planning and asset management can be taken to a new level of precision.

Keywords: Fibre Optics, Fibre Bragg Gratings, FBG, Embedded, Weigh-in-Motion, WIM.

Résumé

Une technologie de mesure utilisant la fibre optique et en particulier les réseaux de Bragg, associée à un système de détection dynamique de grande précision, a démontré sa capacité à capturer avec une haute résolution les déformations d'une route d'asphalte. Les impacts statique et dynamique de pneus sont enregistrés, permettant ainsi de détecter le type des roues, le nombre d'essieux, la vitesse, la bande d'autoroute utilisée, ainsi que le poids des roues, des essieux et du véhicule roulant aux vitesses autorisées sur autoroute. De plus, le système fournit un ensemble de résultats uniques en capturant les déformations de l'asphalte directement sur le site, ce qui inclut l'empreinte et les ondes de déformation du matériau viscoélastique à un niveau de détail sans précédent qui ouvre la porte sur des études poussées de modèles d'asphalte tel que des modèles de prédiction liés à son entretien. Cette capacité à mesurer de manière détaillée la déformation de l'asphalte crée une opportunité significative permettant de suivre l'état des biens appartenant au domaine des routes asphaltées, de telle sorte que le planning d'entretien et de gestion de ces biens soit amené à un nouveau niveau de précision.

Mots-clés: Langue, police, photos, poids lourds, fibre optique, réseaux de Bragg, transport de marchandises, pesage dynamique, WIM.

1. Introduction

Traditionally, weigh-in-motion (WIM) systems have relied on installation of relatively large solid transducers into the surface of the asphalt. This approach relied on electronic, often piezoelectric, recording of the short-term deformation of the installed structure as indication of the weight of the axle that is crossing it transversally. Here, the installed structure, often resembling an I-beam, has acted as a mechanical amplifier or integrator of the signal to allow it to be recorded with the few electromechanical transducer elements installed. While the traditional WIM approach has allowed for measurements at standard traffic flow, it has still been largely affected by the road layers and under construction, its flatness, curvature and weather conditions. As such, the accuracies often achieved in controlled laboratory conditions have not been realized in the field. Furthermore, the need to have surface installed mechanical hardware resulted in both scarring of the asphalt such that it has created locations of crack formation and lifetime shortening. Additionally, the surface embedded systems required full replacement of the hardware in the asphalt, often the expensive part of the system, each time the asphalt top surface has been repaired and re-paved, resulting in high maintenance costs. In this development project, the problem of monitoring loads on roads is approached from a complete new angle, whereby the latest technology developments in fibre optic sensors is leveraged to achieve a high spatial and temporal mapping of the asphalt deformation to enable determination of the localized loads on it.

Here, the key enabling technology for fibre optic sensing employed is Fibre Bragg Gratings (FBGs); wavelength-specific narrow band reflectors formed in the core of standard optical fibre by periodic refractive index variations such that effective wavelengths that are integer multiples of the periodicity get selectively reflected. With broad applications in telecommunication industry, and emerging more recently in sensing applications (Karabacak 2016), FBGs have become valuable tools in fibre optics that can be manufactured reliably and reproducibly at large scale and low cost. Furthermore, such production ability has enabled the manufacturing of an array of reflectors with precisely pre-determined locations and reflection wavelengths in long chains of standard optical fibres. Such arrays allow for highly localized and spatially dense mapping of structural deformations at previously unachieved speeds, enabling novel applications in structural monitoring such as vibration mode mapping. The fundamental features of localized and rapid responsivity of Fibre Bragg Gratings, make them very suitable tools for asphalt and traffic monitoring where at standard traffic flow, events resulting from vehicles passing over sensors is of the scale of milliseconds and effects on the asphalt are highly localized and minimal amplitude yet sufficiently strong to be detectable with FBGs as is demonstrated later.

In the following section, the fundamental underlying technology of FBG-based sensing will be explained, and in section III, the embedding of fibres to asphalt and their setup will be described. Field obtained results in recording of dynamic deformations of asphalt and vehicle property extraction is presented in Section IV, with its implications to enabling a new way of road and traffic monitoring discussed in Section V.

2. Fibre Bragg Gratings and High Resolution Interrogation

As discussed, Fibre Bragg Grating-based sensors requires the tracking of the Bragg wavelengths very accurately, as illustrated in (Figure 1). Typically, each FBG has a characteristics narrow band reflection wavelength, namely the Bragg wavelength, as shown in Figure 1(a), which is defined by the periodicity of the gratings in the fibre core. The periodicity is increased when strain is applied on the fibre and resultantly the Bragg wavelength response is shifted to a higher level, as depicted in Figure 1(b). The Bragg Gratings can be manufactured with their reflection wavelengths being specific and narrowband, such that many non-interfering FBGs are on a single fibre as schematized in Figure 1(c), where each sensing point can be individually tracked accurately and uniquely using a variable wavelength laser system. There exists several approaches to FBG interrogation and while each approach has its advantages, it has been shown that for measurement frequency ranges from static (0 Hz) to low kHz range, which covers the needs of many structural health monitoring applications, use of tunable narrowband laser with broadband detection can achieve Bragg wavelength tracking in the femtometer-level resolutions (equivalent to nanostrain levels of localized fibre strain) with cost effective solid state lasers (Ibrahim, 2016). This dynamic range and resolution enables the ability to record the miniscule deformation of the road in response to individual tyre loads directly and eliminates the need for complex sensing mechanisms, plates and metal constructions to be placed on the surface of the road, like has been previously implemented.

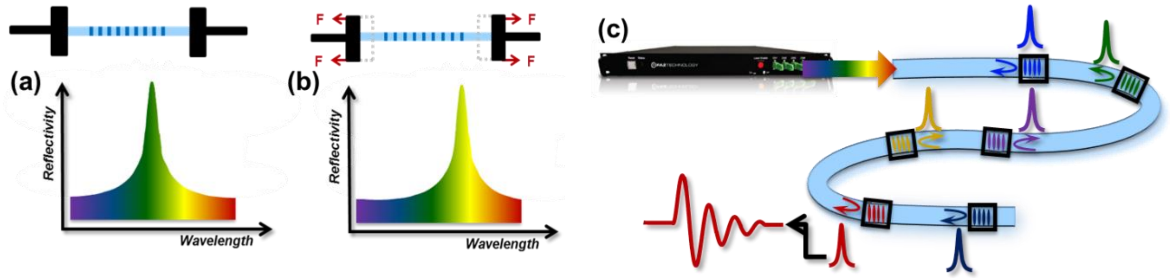

Figure 1 – Fibre Bragg Grating measurement approach where (a) the individual narrowband Bragg reflection wavelengths, (b) which are sensitive to strain, (c) can be arrayed on a single fibre and tracked with a tunable laser system.

Clearly, with the achieved resolution and ability to multiplex and connect many sensors in a chain of fibres enables many structural health monitoring applications from load and deformation monitoring in large assets such as buildings, bridges as well as roads and asphalt. While Fibre Bragg Gratings have been used in many structural (health) monitoring applications using externally attached discrete gauges connected together in a chain by standard communication fibres, applications involving embedding of the fibre with a high density of sensing points directly into the structural material have been more limited, often due to the need to ensure that the fibre is sufficiently robust. Recent developments on specialty coatings on optical fibres with embedded Bragg gratings have led to new generation of sensor arrays that allow for easier handling in the field such as the Fugro AmberCore® strain sensing array with 1 mm outer protective coating (>50 GPa strength) which has been tested in embedding into asphalt and concrete in various applications. By direct embedding of the fibre, as opposed to packaging it into an expensive and bulky metal housing, the FBG technology described here simplifies the installation, results in a better embedded system with minimal damage to the road, longer system lifetime and direct measurement of the road response.

3. Asphalt Embedded Fibre Bragg Grating Array for Vehicle Detection

3.1 The Fibre Optic Sensor Line

In most weigh-in-motion systems, a structural element has been installed into the road such as metal I-shaped beam that essentially acts as a “load integrator” across the width of the lane (or half-lane, depending on the configuration) to generate an electrical signal correlated with the weight. The traditional WIM systems suffer from the exposure to the vehicle impacts, long term effects of the weather and also due to their presence on the surface are highly damaging to the asphalt itself.

In fact, the asphalt itself has a characteristic response to tire loads (as schematized in Figure 2) that can be used in extraction of individual tyre loads if it is recorded with sufficient resolution. However, therein lies a challenge of recording the deformation of the asphalt with sufficient spatial and temporal resolution, without introducing substantial hardware into the asphalt such that its behaviour is altered or its lifetime affected. Fibre optic sensing and FBGs highly suitable as they allow for many sensing points at high spatial density to be formed in a single fibre and recording with high frequency without crosstalk or interference.

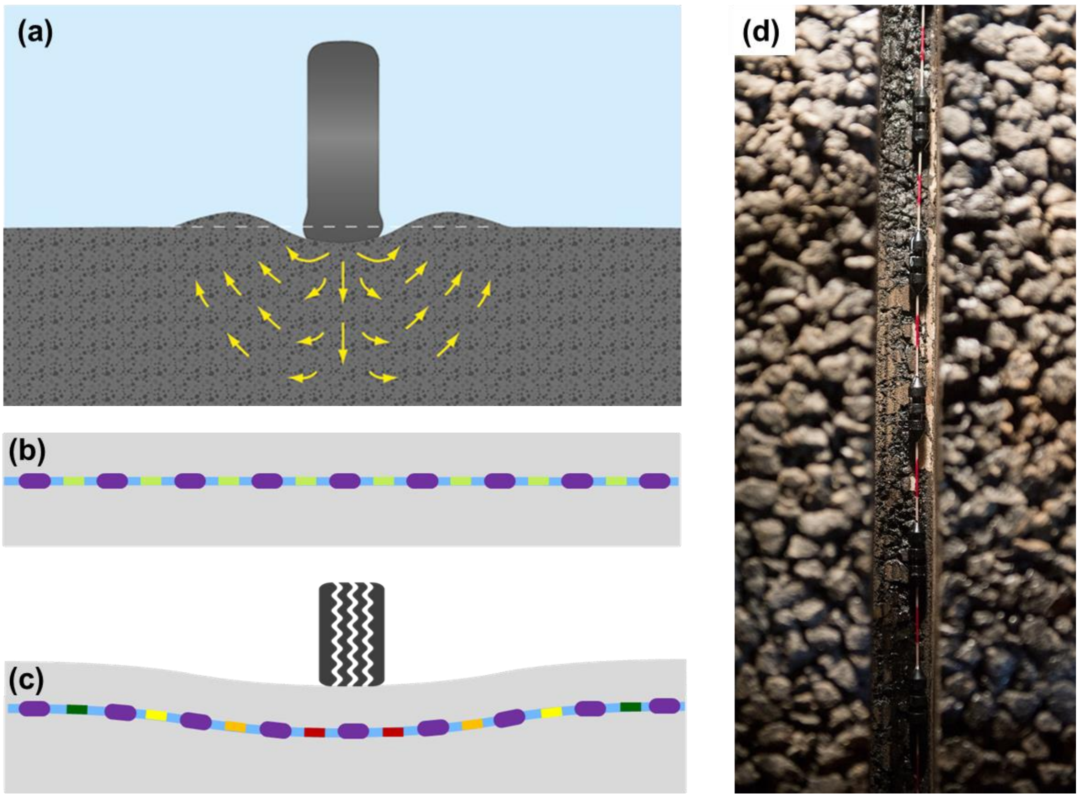

Figure 2 – (a) The deformation due to a tyre load, (b) is recorded with an embedded FBG array into asphalt, (c) with individual sensors recording different strains that map the imprint (d) A typical fibre line placed inside a 15 mm wide groove in asphalt.

A typical installation layout of the fibre in the Fibre Optic WIM (FO-WIM) system is shown in Figure 2(b) where an array of the strain sensitive FBGs are embedded into the asphalt along the width of the lane(s), such that the locally induced deformations of the asphalt is recorded from each point at typically 2000 samples per second. The individual sensing points then record varying lateral strains due to the vertical tyre load, as sketched in Figure 2(c). Typically, the sensing points are spaced 7-10 cm apart although both denser as well as non-equally spaced sensing points are possible to implement and the sensors can be placed in a slit of 10-20 mm wide, preferably as deep as the second layer of asphalt such that scraping and re-paving of the top layer is possible while avoiding damage to the sensors, as shown in Figure 2(d). Typical installation depth is 15-20 cm from the surface of the road and it has been demonstrated that the installation can be paved over by having a top layer asphalt laid down after the fibre has been installed without causing any damage to the system.

3.2 Installation and Recording System

The typical layout of the system is shown in Figure 3, whereby two fibre lines are installed, regardless of the number of lanes, in the road with a separation of 1.5 meters, such that the fibre optic WIM system is also able to extract the speed and the axle distances of the vehicles without the need of additional systems such as induction loops, cameras etc. With the timing accuracies reaching 0.5 milliseconds with the laser system, the vehicle speeds can be resolved to few km/hour accuracies, without the auxiliary systems on site. A license plate recognition camera can be added to the system as an auxiliary unit with time synchronization to enable license plate recognition, vehicle identification and law enforcement, if required.

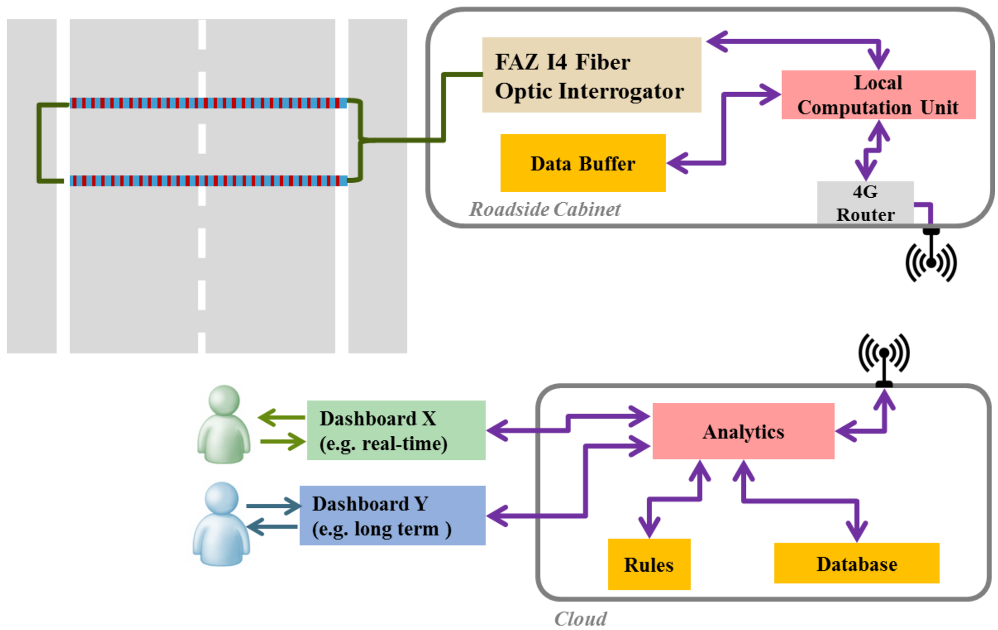

Figure 3 – Typical system layout, with a single loop of fibre embedded connected to a cabinet FAZ Technology recording system and cloud-based data analysis and display.

The two detection lines can contain different sensor configuration and density, depending on the target accuracies and can even contain more lines in parallel if higher accuracies are required as is typical also in traditional WIM systems. In each installation, one or more Fibre Bragg Grating based temperature sensors can also be embedded in the same groove allowing for accurate and localized recording of the temperature of the asphalt layer on the same fibre line. The temperature sensors are also recorded synchronously by the same FAZ Technology I4 interrogator with a 0.1°C resolution, not requiring additional recording equipment, connection lines or challenges of time correlation.

The typical installation procedure of the FO-WIM system only requires two straight saw cuts across the road, possible with single run of the sawing blade on each line due to the narrow width. The sensors are simply laid into the groove, the cabling is routed in a loop fashion allowing for connection from either end. The looping can be avoided if not required or difficult to implement due to certain location limitations. The system can be operated via single port at either end for each line. Standard communication fibre connects the entire system, even if 3 or more lanes, via single cable to the road side cabinet, which can be situated 10s of km’s away if required without substantial signal loss or distortion. The installation of the FO-WIM system is very time efficient in comparison to traditional systems, as both WIM or induction loops which require both larger cuts, and a higher number cuts in a complicated layout, in the case of loops for example. Additionally, the ability to connect all with a single fibre optic cable allows for simplicity of the system. Considering that standard fibre optic lines are cheaper than copper cabling, the system becomes cost efficient to extend over larger distances and scale up to larger installations. Owing to the simplicity of the installation, a typical operation is completed within 2-3 hours of road closure, even for multilane installations, including the cutting, installation, cabling and refilling of the grooves.

4. Detected Signals and Extraction of Vehicle Characteristics

The signal detected from the fibre optic line is essentially lateral strain in the asphalt due to the vertical deformation of the asphalt. A typical signal obtained from one of the field installations on a two lane road due to a compact size car is plotted in Figure 4(a) where each time trace line is acquired from one sensing point. In this road, the vehicle with approximately 300 kg per wheel load generated approximately 4 $\mu\varepsilon$ of deformation recorded at peak. The dual peaks separated by 148 milliseconds are the front and rear wheels crossing the lines, allowing for the length of the vehicle to be calculated to within <10 cm, based on its speed extracted by the time delay between the two lines (not plotted). Additionally, the system has the unique ability to determine vehicle width (track) and its position within a lane, to a very high accuracy. Furthermore, the system has both sufficiently low noise level and high spatial resolution to capture the imprint of a narrow and low amplitude bicycle wheel.

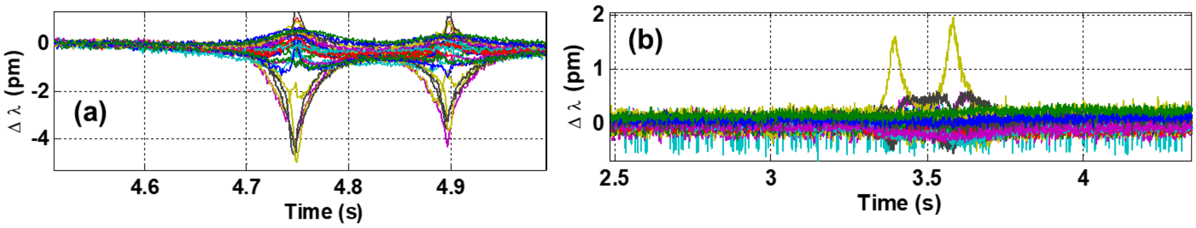

Figure 4 –Typical signals of the fibre optic WIM system in response to (a) a car crossing the line and (b) The signal trace obtained from a bicycle with the same detection line.

The data acquired by all the sensors across time of a vehicle crossing can be stitched together to form a snapshot of the road deformation due to individual vehicles and even individual tyres, as shown for a 5-axle truck in Figure 5. Plots such as these, enable for mapping of the vehicle impact not just locally but also over time, allowing for the first time for asphalt experts to characterize not just the elastic behaviour of asphalt but also its viscoelastic characteristics, in situ, over different temperatures and loads. Furthermore, by recording the imprint of the individual tyres, the system allows for identification of the wheel types such as single wheels, double wheels or wide tires.

For the wheel force to be determined from the measurements, a relationship between transversal strain and the wheel force is established. The Boussinesq solution for a force on a half space forms the basework of the simulation (Burmister 1945b). With Odemarks layer theory taken into account variables are set in the equation which allow the local pavement structure to be determined via calibration runs. Three sites have been installed on several locations on the Dutch highway near Rotterdam in open asphalt as field trial of the technology for weigh-in-motion in highway traffic conditions with the local pavement structure consisting of 310 mm asphalt on main roads and 225 mm on parallel roads on top of a base layer of 250 mm hydraulic mixed granulate on compacted sand. The fibres are embedded in the asphalt at 15 cm depth.

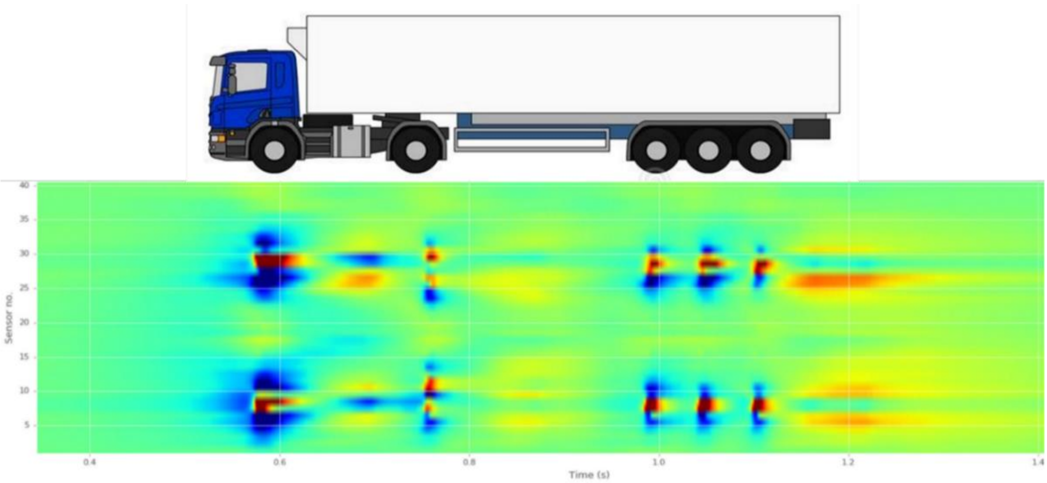

Figure 5 – The lateral strain imprint of a 5-axle truck (>80 km/hr) recorded on the fibre optic WIM system stitched together from the set of data recorded from 40 sensors, with the colours indicative of the lateral strain (red: tensile, blue: compression, green: zero).

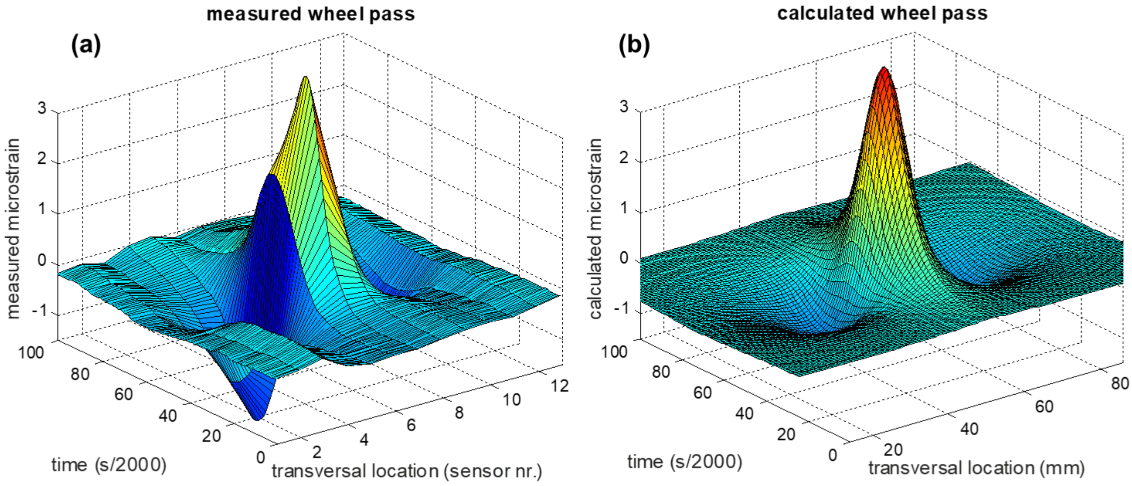

Figure 6 – (a) Plot of the recorded lateral strain due to a 920 kg wheel weight and (b) the theoretical plot with only scaling of fitting parameters based on the calibration.

There are other factors, besides the wheel force, that directly influence the measurements. The local pavement structure varies lightly across the pavement, either due to construction margins or different use of the road however to a large extent these variables are perceived to remain constant. The main variable contributors have been found to be the asphalt temperature, the wheel speed and the transversal location of the wheel in relation to the sensor. The difference caused by a local difference in pavement structure has been corrected for directly by use of calibration runs, discussed further below. The variables asphalt temperature and wheel speed are corrected for simultaneously by use of the correlation between asphalt temperature and wheel speed, and the asphalt concrete stiffness. Layer theory of Odemark shows a relationship between the occurring strain and the stiffness of the top layer, which allows for correction of temperature and speed via a correction on the asphalt layer stiffness. This requires input on the asphalt concrete material behaviour. The mixture properties as decided in the standardised Dutch design method show a good correlation for this (CROW 2012). The difference caused by the transversal location of the wheel is (whether the wheel is right on top of a sensor, or in between two sensors) is solved by fitting the derived function to the measurements instead of dealing with the individual measurements directly. The simulations done based on the asphalt structure of one of the installation sited provide a very close correlation with the detected signals shown in Figure 6 for a wheel (recorded at 91 km/hr) and the theoretical prediction with only the scaling factor used.

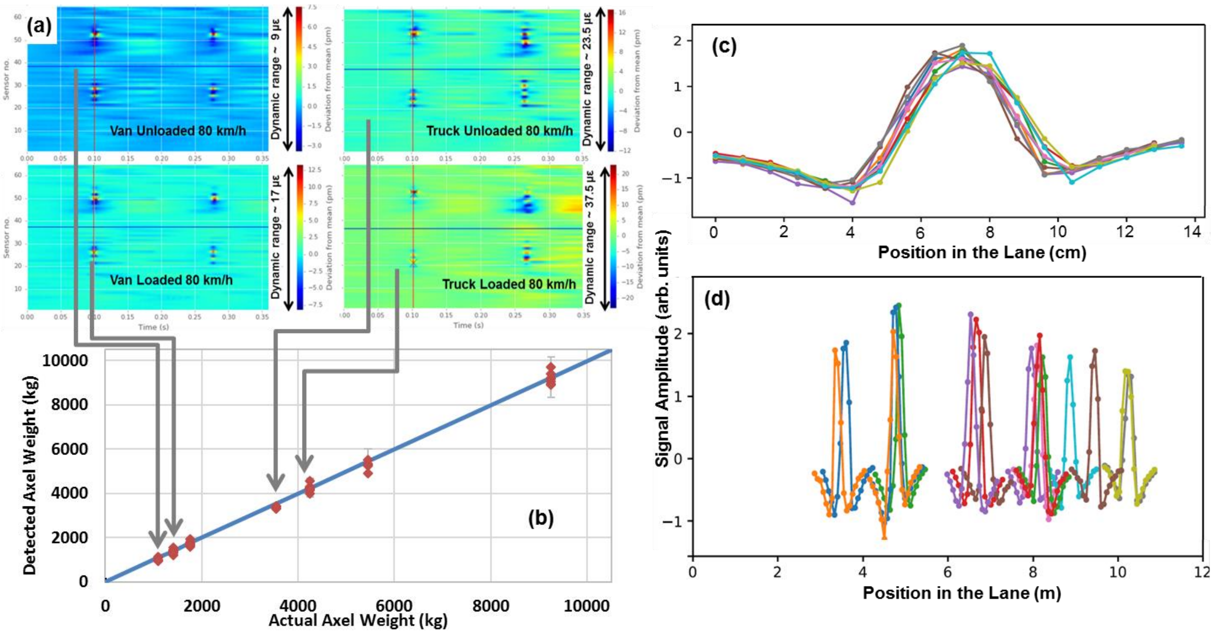

Figure 7 –(a) Imprints recorded from calibration vehicles traveling at 80 km/hour, (b) the weight results extracted. The repeatability of 10 signals recorded from identical wheel (c) across the same sensor location and (d) varying locations on a 3-lane road.

The system can be calibrated in-situ, as is often done for the traditional WIM systems also, by driving over with vehicles with a calibrated load at each wheel, at various speeds. Several calibration runs are typically performed over different temperature periods. The localized response of the road layers for a given load and temperature are used in the algorithms to extract the wheel loads during the operation of the system. The detected signals from differently loaded vehicles, shown in Figure 7(a), have been demonstrated to be closely correlated with the loads on the road due to each vehicle, as shown in Figure 7(b). The repeatability of the system has been also demonstrated to be very high for each sensor location as shown in an exemplary data set plotted in Figures 7(c) for the sensor line across the lane for 10 recordings of the same wheel and loading crossing at identical speeds. Figure 7(d) plots the responses recorded at different locations in the 3-lane road for the same wheel imprint. The results show that different locations in the road have different responses as would be expected due to the underlayers, and that these can be corrected for by the calibration run as shown above where response to the same load is recorded and correction factors are extracted for each installation site. With the approach demonstrated above, the axle load accuracies that correspond to C-class in COST323 (Jacob, 2000) can be reached and several points of improvement have been identified to enable further increases in accuracy to reach B-level.

As with all WIM systems, there exists important data corrections to be performed to compensate for the temperature, speed and other effects in the system. Leveraging the asphalt behaviour as the detection mechanism certainly introduces even more challenges in the data analysis owing to the fact that asphalt demonstrates strongly temperature dependent viscoelastic characteristics. On the other hand, the high spatial and temporal data collection enabled by the FO-WIM system allows for a rich data set to be obtained with multiple features to be used for these corrections, such as the relaxation characteristics of the asphalt (noticeable in Fig. 2 and 5) and spatial variations in sensitivity as shown in Figure 7(d). The (cloud-based) data analysis system implemented essentially formulates the correction factors based on temperature (recorded via embedded fibre optic gauges), speed (obtained from the dual line configuration) and position of the wheel on the lane (resolved from the recorded strain maps). The controlled data set obtained from calibration runs covering each parameter is mapped onto a multi-dimensional correction factor (scaling) function, as schematized in a simplified form in Fig. 8. In Fig.8(b), a spatial correction factor is demonstrated where the "softness" of the road across the lanes is corrected for by the signal levels extracted from the calibration wheel crossings plotted in Fig. 7(d). By use of the theoretical functions for the temperature, speed and spatial influences and pinning those down with a set of calibration functions, accurate corrections can be achieved. Furthermore, the scaling functions can be turned into adaptive functions such that as the asset changes the correction factors adapt accordingly, either via regression approaches or machine learning. In particular, pavement fatigue will also occur over longer periods (especially in the truck lane), this will manifest itself in a decrease of the local asphalt stiffness. The changes in the asset over long life can be detected either via periodic calibrations or even by automatic detection of specific features such as static strains and stresses in the material. The changes in the needed scaling functions can be valuable indicators of asset and material degradation for asset managers.

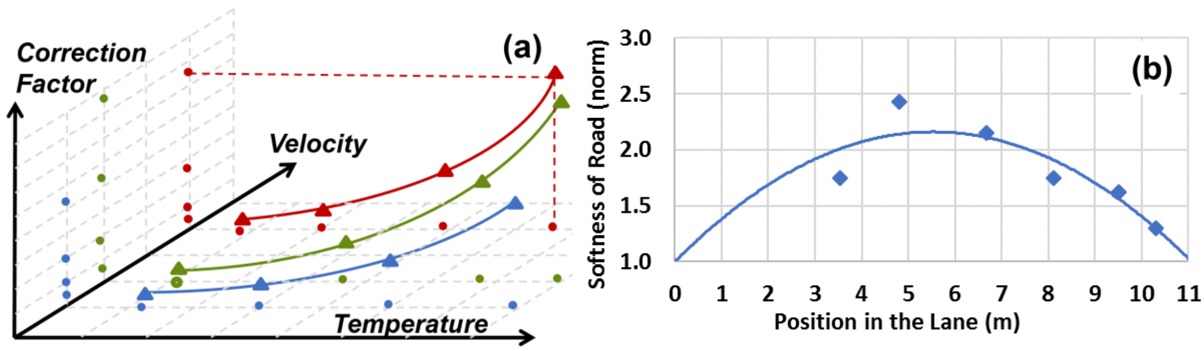

Figure 8 (a) Multiple correction factors based on temperature, vehicle velocity, sensor position (not shown) are calculated based on calibration runs (triangles) (b) Typical location based calibration factor for the normalized softness of a 3-lane highway.

Finally, it is important to note that the typical installed system generates about 100 GB/day per lane of road monitored. The optimized detection algorithms continuously operating on the computer in the roadside cabinet digest the information, detect the vehicles, record their impacts and compress the data by orders of magnitude, to allow for the road deformations per each wheel to be communicated via GSM network to the cloud where they are stored and analysed further to extract vehicle information such as speed, axle count, axle distances, weights etc. The information database generated allows for statistical analysis to be performed depending on the user needs, which can be viewed online via a webportal. The system is built with data buffers to handle communication channel congestion or downtimes such that data loss is prevented.

5. Conclusions

The innovative fibre optic WIM system presented here is clearly an integrated method for extracting a multitude of valuable information for asphalts in real-time. By recording the strain imprint of each wheel with such high temporal and spatial resolution, the approach presented allows for detection of the vehicle characteristics such as its axle loads, speed, distance between axles as well as wheel-specific information with a single integrated system that is least damaging to the infrastructure. The system is capable real-time information valuable for traffic management and enforcement without requiring complementary induction loops to be installed at the sites, simplifying the installation procedure, eliminating top surface installation needs, reducing installation and hardware cost and simplifying the data acquisition system to a single unit that can collect all needed information from single point. Furthermore, the fibre optic weigh-in-motion system presented here provides a totally novel system that is efficient and simple to install. By avoiding complex and expensive equipment in the asphalt with moving components, the system becomes both cost-effective as well as long lifetime and any parts that may require adjustments, replacements and repairs are shifted to the more easily accessible road-side cabinets.

It is also important to note that the fibre optic WIM system has been installed during the construction of the road, such that the top asphalt layer was constructed after the installation of the fibre and the system has fully survived the asphalt paving operation on top, without loss of even single sensing point. This allows for embedding of the fibre optic WIM system in the construction phase such that even the top surface cutting can be avoided and a perfect continuous “scar free” pristine asphalt condition can be obtained on top layer which will allow for longer lifetime for both the asphalt and the embedded WIM system. Furthermore, the ability to have the system either in the sublayer or only with narrow line on the asphalt, the entire weighing system can be made very discrete such that it is not detectable by the drivers, and hence prevent avoidance or misleading of the detection on purpose.

Most importantly, however, the FO-WIM system provides information for the asphalt and pavement engineers, as well as asset owners, that has been previously lacking. In contrast to the traditional systems which record the deformation or load on an artificially introduced mechanical structure, the FO-WIM system records the actual and accurate deformation of the asphalt layers. As such it allows for characterization of the actual road layers as opposed to relying on models and predictions. Furthermore, by accumulating the deformations and stresses the asphalt has experienced over time and with the localization possible, it will allow asset managers to both understand their asset as well as its wear and tear in reality. Such tools can allow for optimization of asphalt compositions and underlayers for specific locations as well as optimization and accurate planning of maintenance cycles, allowing for both cost savings as well as preventing of degradation before repair, essentially allowing the asset owners of roads to switch from operating in scheduled maintenance mode to preventive and predictive maintenance operations.

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Specifications for Multi-Brand Truck Platooning



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Abstract

Platooning technology has made significant advances in the last decade, but to achieve the next step towards deployment of truck platooning, an integral multi-brand approach is required. It is the ambition of ENSEMBLE to realize pre-standards for interoperability between trucks, platoons and logistics solution providers, to speed up actual market pick-up of (sub)system development and implementation, and to enable harmonization of legal frameworks in the member states. This paper provides with definition of the specifications of the whole multi-brand truck platooning concept to be implemented within the testing and demonstration trucks of the 6 OEMs. It describes the functional architecture, captures all minimum set of operations layer requirements and tactical layer specifications for Platoon level A. The building blocks of truck platooning consist of in-vehicle requirements (Longitudinal, sensors, HMI interaction), infrastructure (V2I), information among trucks in platoon, and platooning strategy (coordination mode, gap regulation, formation, dissolution, and vehicle mix).

Keywords: truck platooning, specifications, automated driving.

Résumé

La technologie de peloton a fait des progrès significatifs au cours de la dernière décennie, mais pour franchir la prochaine étape du déploiement de pelotons de camions, une approche multimarques intégrée est indispensable. Le projet ENSEMBLE a pour ambition de mettre en place des pré-normes en matière d'interopérabilité entre les camions, les pelotons et les fournisseurs de solutions logistiques, d'accélérer le développement et la mise en œuvre de (sous-) systèmes sur le marché et de permettre l'harmonisation des cadres juridiques dans les États membres européens. Ce document fournit une définition des spécifications du concept de groupement de camions multimarques à mettre en œuvre dans les camions de test et de démonstration des 6 constructeurs. Il décrit l'architecture fonctionnelle, capture l'ensemble des exigences minimales de la couche d'exploitation et des spécifications de la couche tactique pour le niveau A. Les éléments constitutifs du groupement de camions sont les exigences embarquées (longitudinal, capteurs, interaction IHM), infrastructure (V2I), informations entre camions du peloton et stratégie de peloton (mode de coordination, régulation des écarts, formation, dissolution et combinaison de véhicules).

Mots-clés: peloton de camion, spécifications, conduite automatisée.

1. Introduction

Platooning technology has made significant advances in the last decade, but to achieve the next step towards deployment of truck platooning, an integral multi-brand approach is required. Aiming for Europe-wide deployment of platooning, 'multi-brand' solutions are paramount. It is the ambition of ENSEMBLE to realise pre-standards for interoperability between trucks, platoons and logistics solution providers, to speed up actual market pick-up of (sub)system development and implementation and to enable harmonisation of legal frameworks in the member states.

1.1 Main goal of ENSEMBLE

The main goal of the ENSEMBLE project is to pave the way for the adoption of multi-brand truck platooning in Europe to improve fuel economy, traffic safety and throughput. This will be demonstrated by driving up to seven differently branded trucks in one (or more) platoon(s) under real world traffic conditions across national borders.

When evaluating the different platooning projects such as CHAUFFEUR II (2000 - 2003), KONVOI (2005 - 2009), SARTRE (2009 - 2012), i-GAME (2013 - 2016), COMPANION (2013 - 2016), AUTONET2030 (2013 - 2016), ROADART (2015 - 2018), CONCORDA (2017 – 2020), it can be seen that these projects mostly concentrate on developing the in-vehicle platooning technology, whereas later projects more concentrate on either a specific technological challenge (e.g. antennae design and placement) or on the use of platooning technology (e.g. platoon coordination). With respect to use cases and in-vehicle architectures, many commonalities are seen on a high level. However, details are often not published. This also holds for the low-level controllers used in the different projects. Moreover, tactical layer functionalities and operational layer functionalities have mostly been implemented as one 'controller', i.e. there was no separation between 'common' and 'truck specific' functionalities, which is needed for ENSEMBLE's tactical and operational layers. Hence, a clear task is reserved for ENSEMBLE to separate these functionalities in a way that the technology is still usable for all OEMs. Besides that, the impact of non-homogeneous platoons is still unclear. Heterogeneous platooning may stem from different sources: different operational implementations (spacing policies, control algorithms and information used for control, for instance), different vehicle capabilities in accelerating and decelerating (vehicle total mass, available engine power, brake capacity). Additionally, road profile may affect platoon performance. Despite the substantial academic work on platooning, applied control design for (heterogeneous) platooning is still an open issue. Only very limited publications deal with implementation relevant aspects and/or heterogeneity of platoons. This thus is still an open area also for ENSEMBLE.

1.2 Platooning levels and SAE

In order to break down the complexity of deploying multi-branded truck platooning on public roads different platooning Levels are defined. The Platooning Levels facilitate a stepwise approach to deployment of platooning on public roads, where the "first" Platooning Level defined in ENSEMBLE can be deployed in the *near* future. The idea of Platooning Levels has emerged since the commonly accepted automation levels of the SAE J3016 have shortcomings when applied to platooning. The first level in the SAE levels of driving automation involves either longitudinal or lateral vehicle automation, whereas the driver is responsible to detect safety-critical events and take appropriate action. Level 2 involves both longitudinal and lateral automation, with the same driver responsibility as in level 1. In level 3, the driver responsibility is decreased to only act upon a warning by the automation system. Only in level 4 and higher, the driver has no driving task anymore for part or all of the journey. Truck platooning, however, involves driving at short inter-vehicle distances for an extended period. Therefore, the driver cannot be held responsible for timely intervention in case of safety-critical events such as hard braking. Furthermore, the platoon as a whole can be seen as a system of interconnected systems with specific requirements. Hence, the first three SAE automation levels are not directly applicable for the platooning application. Consequently, the need arises to create a different automation level classification for heavy duty vehicles that considers the explained needs of Platooning. The definition of "platooning levels of automation" will comprise elements like the minimum time gap between the vehicles, whether there is lateral automation available, driving speed range, operational areas like motorways, etc.. Three different levels are seen for now – called platoon level A, B and C.

Table 1-High level platoon levels overview

	Platoon level A	*Platoon level B*	*Platoon level C*
Longitudinal automation	Leading truck: manual or advanced assist system (e.g. ACC) Following & trailing vehicle: Autonomous longitudinal control (CACC, CAEB, Cxxx, ...)	*Leading truck: manual or advanced assist system (e.g. ACC)* *Following & trailing vehicle: Autonomous longitudinal control (CACC, CAEB, Cxxx, ...)*	*Leading truck: manual or advanced assist system (e.g. ACC)* *Following & trailing vehicle:Autonomous longitudinal control (CACC, CAEB, Cxxx, ...)*
Lateral automation	Driver Optionally: in lane by system (standalone vehicle)	*In lane + lane changes (coordinated)*	*Full automation from A to B*
Operation area	Triggered by driver in dedicated areas (e.g. highway)	*Dedicated areas (e.g. highway)*	*Dedicated areas (e.g. highway + parking areas)*
Fault tolerance	Longitudinal degradation functionality	*Longitudinal & lateral degradation functionality*	*Longitudinal & lateral degradation functionality*
Platoon engaging	Only from behind (by single truck & existing platoon)	*From behind (by single truck & existing platoon) and from the front by single truck*	*From behind (by single truck & existing platoon), from the front by single truck and merging of single trucks in existing platoon*
System & environment monitoring	System itself + Driver (environment)	*System itself*	*System itself*
Fallback of the DDT (dynamic driving task)	Driver; as long it is safe and the driver can react in time	*System (for x seconds)*	*System*
Safe state	Fail-safe (driver in control after reaction time of the driver)	*Stopped in ego lane or rightmost lane*	*Stopped in safe stop area (e.g. fuel station)*
Timegap (Steady state @ 80 kph)	>0.8s	*>0.5s*	*>0.3s*
Maximum number of trucks	7 (maximum for simulations & verifications)	*No principle technical limitation as for now*	*No principle technical limitation as for now*
Platoon formation (orchestrated) possible	Yes	*Yes*	*Yes*

2. Functional Architecture

The white label truck representing a brand-less truck that has all the described specifications, Figure 1 gives an overview of the elements of the white label truck. The white label truck on the one hand comprises specifications: these are mainly elements specifically added for platooning. On the other hand, it comprises requirements: here OEM specific systems or connections to OEM specific systems are involved

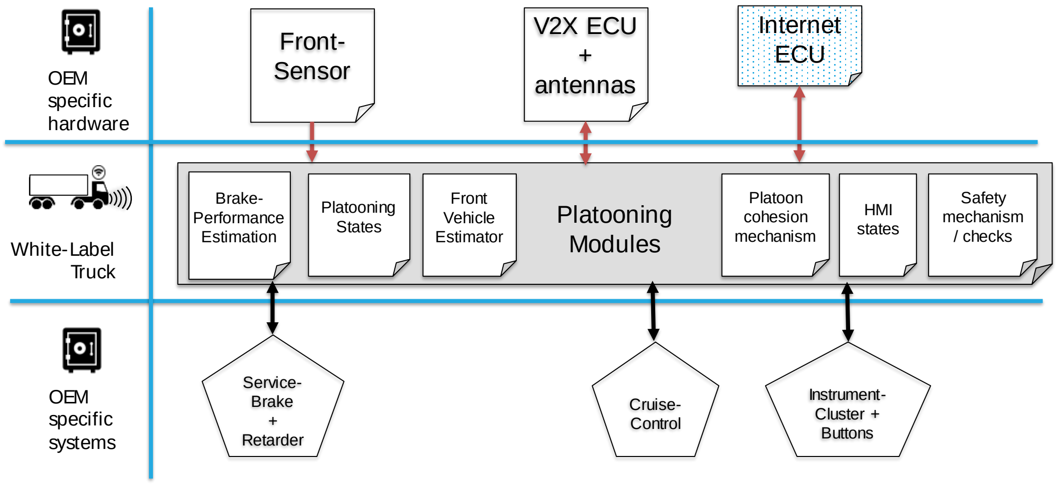

Figure 1- Elements on the white label truck

2.1 Platooning layers

The concept of the ENSEMBLE platooning system consists of a hierarchical system, with interacting layers. The envisioned concept is presented in Figure 2.

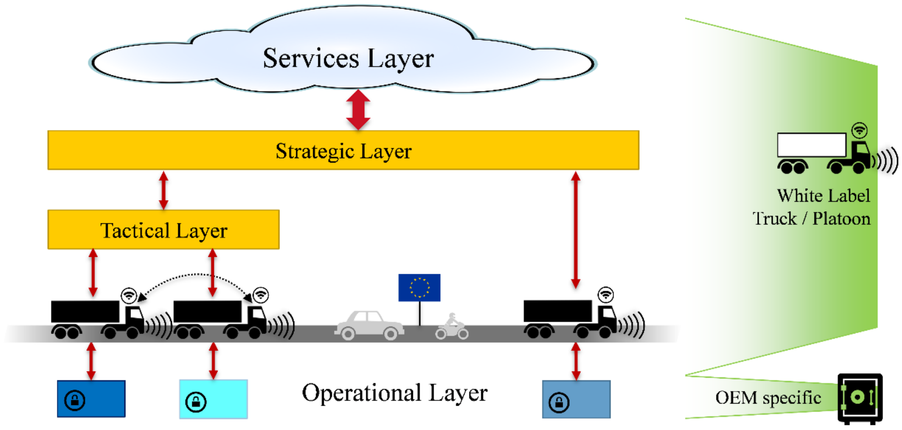

Figure 2 - ENSEMBLE platooning layers

The different layers have the following responsibilities:

- The service layer represents the platform on which logistical operations and new initiatives can operate.
- The strategic layer is responsible for high-level decision-making regarding scheduling of platoons based on vehicle compatibility and Platooning Level (see below), optimisation with respect to fuel consumption, travel times, destination, and impact

on highway traffic flow and infrastructure, employing cooperative ITS cloud-based solutions. In addition, the routing of vehicles to allow for platoon forming is included in this layer. The strategic layer is implemented in a centralised fashion in so-called traffic control centres. Long-range wireless communication by existing cellular technology is used between a traffic control centre and vehicles/platoons and their drivers.

- The tactical layer coordinates platoon forming (both from the tail of the platoon and through merging in the platoon) and platoon dissolution. In addition, this layer ensures platoon cohesion on hilly roads, and sets the desired platoon speed, inter-vehicle distances (e.g. to prevent damaging bridges) and lateral offsets to mitigate road wear. This is implemented through the execution of an interaction protocol using the short-range wireless inter-vehicle communication (i.e. V2X). In fact, the interaction protocol is implemented by message sequences, initiating the manoeuvres that are necessary to form a platoon, to merge into it, or to dissolve it, also considering scheduling requirements due to vehicle compatibility.
- The operational layer involves the vehicle actuator control (e.g. accelerating/braking, steering), the execution of the manoeuvres, and the control of the individual vehicles in the platoon to automatically perform the platooning task. Here, the main control task is to regulate the inter-vehicle distance or speed and, depending on the Platooning Level, the lateral position relative to the lane or to the preceding vehicle. Key performance requirements for this layer are vehicle-following behaviour and (longitudinal and lateral) string stability of the platoon, where the latter is a necessary requirement to achieve a stable traffic flow and to achieve scalability with respect to platoon length, and the short-range wireless inter-vehicle communication is the key enabling technology.

The white-label truck concept encompasses both the tactical and the strategic layer, whereas the operational layer will be brand specific and the services layer will focus on logistics, hence being unbranded. Hence, ENSEMBLE multi-brand truck platooning concept takes into consideration Platoon level A (e.g. driver responsibility) which will form the basis of the intended demonstration at the end of the project on public road.

3. Multi-Brand truck Platooning Specifications

Summarizing, D2.4 captures all minimum set of operations layer requirements and tactical layer specifications for the white label truck platooning concept. The building blocks of truck platooning consist of in-vehicle requirements (Longitudinal, sensors, HMI interaction), infrastructure (zone policy), information (ranging, V2V and V2I exchange, and data sharing), and platooning strategy at tactical layer (coordination mode, gap formation, dissolution, and vehicle mix).

The tactical layer coordinates the actual platoon forming (both from the tail of the platoon and through merging in the platoon) and platoon dissolution. Related to platoon manoeuvre coordination, specifications indicate that the platoon shall have awareness of the status of the coordinated gap opening on platoon level and the target vehicle reports to the following vehicle the status of the gap opening procedure. During gap opening, the speed of the leader vehicle is distributed over the whole platoon. The tactical layer will gather several platoon status items (e.g. ego vehicle position) and distribute this over the platoon in a hopping type of method and this information is updated with a rate of 1 Hz. The tactical layer shares the vehicle status information in an equal method within the platoon as the platoon status and this information is updated with a rate of 1 Hz. The setpoint limit/advice function will be send to the operational layer the combined advised value for the vehicle set speed and time gap as processed from information from the strategic layer and the platoon status. The requirements simulation process is supported by first-principles simulation in order to perform a reality check on the feasibility and the relevance of the specifications.

In order to allow an interaction with the trucks in the platoon, a communication link must be established between the platoon participants. The decentralized tactical layer running locally in the trucks needs information from the other trucks. Therefore, also the state machine on vehicle level is introduced.

For Platoon Level A, the Road Side Unit have been selected for the implementation of communication between the platoons and the infrastructure. The information that is needed is the ability for the individual vehicles of the platoon to receive communications on policy based on zone (zone policy or geofencing) and constantly to be up to date (refresh period to be defined). In addition, the ability for the individual vehicles of the platoon to adjust speed based on zone policy and interdistance based on zone policy is also an additional specification.

The requirements for the in-vehicle hardware components which are specific for platooning can be grouped into the following categories:

- HMI – the driver interface to the vehicle and in particular the platooning solution
- Longitudinal control system consists of sensors, control computation and communication and control actuation components.

The common HMI-logic should function as the "lowest common denominator" for each OEM's HMI-design for platooning, regardless truck brand. The purpose of the common HMI-logic is to provide a structure for coherent interactions between the driver and the platoon system and still allow for OEM specific solutions.

Longitudinal control requirements are divided among requirements for how the minimum inter vehicle time gap is selected, requirements for safely handling braking in the platoon, requirements for how to increase the inter vehicle time gap in a safe way and requirements for how to close gaps and keep the platoon together. The latter one describing the platoon cohesion functionality is summarized in two requirements, where the first requirement is aiming for solving an existing cohesion issue, whereas the second requirement is about avoiding cohesion issues to occur. As regards sensing specifications, this report gave a focus to the sensor data and associated sensors required for a white label solution to assess the environment and which are specific for platooning. It was concluded that radar technology best fulfils the requirements for distance keeping in a platoon. V2X communication is also mandatory inside a platoon and can be used also as sensor functionality.

4. Axle loads and weigh-in-motion

4.1 Weigh-in-motion systems

Loads (axle loads or GVW) of the trucks with one multi-brand platoon can be obtained through various means:

- The loads can be obtained from weigh-in-motion systems installed on the road infrastructure, meaning in-pavement sensors or bridge weigh-in-motion. These solutions are especially interesting for road authorities, as a direct access to the data is always possible.
- Axle loads can also be obtained through on-board weighing which is installed on the axles on trucks, often originally on modern trucks. This data may be used directly by trucks for their route planning, or by road authorities by modalities for this data sharing have been installed.

4.2 Utility of loads

Axle loads do have several uses, for example:

- Some parts of the road infrastructure may not be able to cope with all types of platoons, because of the associated damage. For these, geofencing may be linked to the GVW and axles loads of the trucks with the platoon. In this case, communication V2I will be needed, and I2V for giving the driving instructions.
- Axle loads and GVW are also important for the platoon itself. Indeed, braking distances are linked to the carried loads, and the braking power of the truck. Therefore, it might be better to put a light truck with good braking distance, after a heavily loaded truck with weak braking power.

5. Conclusions and next steps

Finally, specifications are going to provide the specified functionalities for the project to implement and demonstrate in 2021. Verification and validation phase of the functionality of the equipped vehicles will be verified against the specifications and the developed functionality will be compared to the intended multi-brand functionality to validate the results. A list of KPIs like e.g. in impact of platooning on traffic flow, bridges, other road-user's behaviour, impact on the environment, possible business cases will be mapped against requirements. Finally, the requirements are consolidated towards pre-standards and recommendations and guidelines and are developed for future policy and regulatory frameworks for the wide scale implementation of multi-brand platooning. The updated report will provide with a mapping and gap analysis between the specified requirements and specifications and standardisation and regulation. The iteration process to validate and modify the specification during the whole project life-cycle is an essential part of the work.

There are still however open issues that need to be resolved and assumptions taken. The requirements are written as if the system is responsible because that is still the agreement for Platooning Level A and vision of the ENSEMBLE project. If the system is responsible it will probably put very strict requirements on the system, such as high accuracy brake capacity estimation and very high reliability on always being able to brake. This remains the task to be further defined for Platoon level B and C the definitions and use cases detailed in D2.3 and their respective requirements and specification which will be reflected in D2.5. For the platooning demonstration it is planned to use the actuators which are present in state-of-the-art vehicles. Thus, there are no specific requirements for the time being. This could change over time once the results of the HARA and SOTIF analysis are available. The communication requirements are already documented in other reports.

The HMI-logic presented in this deliverable is based on the current knowledge from platooning and from general Human factors guidelines in the field of driver-automated vehicle interaction. The HMI-logic has not been evaluated and validated, for example in field tests or in simulator studies and, therefore, should be regarded as a draft and subject to changes as platoon systems are tested and evaluated from technical as well as from user (driver) point of view. Moreover, the HMI-logic is on a high level and does not stipulate specific messages, icons, symbols, colors or if and how multi-modal output (sounds and haptic) should be used to enhance the driver-platoon system interaction. These issues are important to investigate further once the overall HMI-logic is in place and be subjects for standardization. The results from the interviews with platoon drivers indicated that the verbal communication (via radio) between the drivers was important to maintain the platoon and to handle situations, such as Cut-ins, obstacles ahead, traffic at exits and entries etc. However, it is most likely drivers in future platoons speak different languages and don't understand each other. Therefore, the safety of a platoon should not be dependent on verbal communication between the drivers.

Another open issue is how drivers can recognize which truck(s) on the road is a pending co-platoon truck. This is also the case while driving in a platoon, i.e. how to know that the truck in front of the ego-truck is part of the platoon (and not a cut-in). A subsequent question is if and how other co- road users need to be informed about platoon driving on the road. Driver and system roles and task, the term "responsibility" is deliberately not used, because "responsibility" infers legal matters and not HMI-matters. The responsibilities of the driver and the platoon system in different use cases and possible critical incidents should be investigated from a legal point of view (not from an engineering or HMI-point of view).
Another consideration is that the definition of the specifications of the whole multi-brand truck platooning concept have not yet been mapped across functional safety analysis and SOTIF in order to assure that the white label truck platooning concept functions and acts safely during normal operations. The ENSEMBLE project will analyse the safety risks related to both functional safety and SOTIF and derive requirements to lower these risks to an acceptable level. Since these activities will not only define requirements for hazards arising from E/E malfunctions but also address hazards resulting from performance limitations or insufficiencies of the function itself, the safety activities carried out for the project are enough to have a safe platoon deployment on public roads. Functional Safety and SOTIF activities, will define new requirements and may restrict current Platoon Level A definition.

In addition, to that the project is going to assess how these specifications have impact to weight in motion strategies. Moreover, another important issue is that regulation and requirements by the road authorities and member states might also generate additional requirements and might impact testing and verification of trucks platooning systems on the roads. The project has also foreseen to organize in second quarter of 2019 a common workshop among the European Truck Platooning challenge (ETPC), C-Roads Platform, CONCORDA, CEDR in order to validate the ENSEMBLE requirements and to ensure convergence and agreement on the V2I topic and to suggest a unique proposal for the European Commission.

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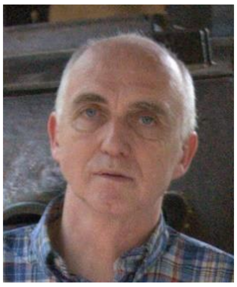
Session 6 : WIM Data for Bridges

Chair: Franziska Schmidt (IFSTTAR, France)

STATISTICAL APPROACH TO BRIDGE HEALTH MONITORING USING AN ACCELERATION-BASED B-WIM SYSTEM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Abstract

This paper develops a Bridge Weigh-in-Motion (B-WIM) system based on the acceleration response of the bridge. The objective is not to measure vehicle weights but to use the mean calculated weights as an indicator of the bridge health condition, i.e., for Bridge Health Monitoring (BHM). The statistical properties of traffic at a bridge site (for example, the most frequent GVW of 3-axle trucks) tend to be consistent, so, if inferred vehicle weight is sensitive to bridge damage, the mean weight can be a useful indicator of bridge condition. Traditional B-WIM systems are developed on the basis of bridge strain responses, which provide accurate axle and Gross Vehicle Weights (GVWs) for a healthy bridge. However, strain is not damage sensitive, so acceleration is used here. The new B-WIM system is found to be inaccurate but to be consistently so and the statistical properties of inferred weights are found to be sensitive to bridge damage.

Keywords: Weigh-in-Motion, WIM, Bridge Weigh-in-Motion, B-WIM, Bridge Health Monitoring, BHM, SHM, Acceleration.

Résumé

Ce papier développe un système de pesage en marche par pont instrumenté (B-WIM) basé sur la réponse en accélérations du pont. L'objectif n'est pas de mesurer le poids des véhicules, mais d'utiliser les poids moyens calculés comme indicateur de l'état de santé du pont, c'est-à-dire pour le suivi de la santé du pont (BHM). Les propriétés statistiques du trafic sur un site de pont (par exemple, le poids à vide le plus fréquent des camions à 3 essieux) tendent à être cohérentes. Ainsi, si le poids inféré du véhicule est sensible aux dommages sur le pont, le poids moyen peut être un indicateur utile de l'état structurel du pont. Les systèmes B-WIM traditionnels sont développés sur la base des réponses de déformation du pont, qui fournissent des poids de charge bruts et des essieux précis pour un pont en bonne santé. Cependant, la déformation n'est pas sensible à l'endommagement, l'accélération est donc utilisée ici. Le nouveau système B-WIM s'avère inexact mais cohérent, et les propriétés statistiques des poids inférés se révèlent sensibles aux dommages causés aux ponts.

Mots-clés : Pesage en marche, WIM, pesage par pont instrumenté, B-WIM, surveillance de l'état des ponts, BHM, SHM, accélération.

1. Introduction

Road bridges are important structures which require continuous monitoring to ensure their safety. Bridge structures deteriorate with the passage of time due to corrosion, accentuated by micro-cracking resulting from traffic loading (Richardson, Jones, Brown, O'Brien, & Hajializadeh, 2014). There are various Bridge Health Monitoring (BHM) methods, including visual inspection, and various arrangements of sensors. Visual inspection is the most frequently used approach to BHM, but it is time-consuming, may be disruptive to traffic and is subjective (Malekjafarian, McGetrick, & OBrien, 2015).

Direct instrumentation uses sensors (commonly strain gauges) on the bridge to acquire the bridge responses to passing traffic. Strain transducers can be used but, to be effective in detecting damage, they must be installed at (or near to) the location of the damage (Cantero & González, 2014). Distributed arrays of sensors are possible but are difficult to manage and time-consuming to install.

The responses to passing traffic are analysed here using the Bridge Weigh-in-Motion (B-WIM) concept which is a technique for estimating the axle and gross vehicle weights (GVWs) of crossing vehicles (González, 2010). Here B-WIM is used as a means of processing the strain responses to random traffic. B-WIM converts raw strain signals, which vary due to the differences in axle weights, spacings, etc., into GVWs which tend to be more consistent, statistically. The B-WIM concept works on the principle of minimizing the sum of squared differences between the measured and theoretical responses of the bridge to the vehicle. The theoretical response of a vehicle is a function of each axle weight and bridge influence line response (Moses, 1979). Traditional B-WIM systems use strain responses for calculating GVWs, but strain responses are not damage sensitive, unless the sensor is very close to the location of damage. Acceleration responses, on the other hand, are sensitive to the bridge damage at any location and have the potential to be used for effectively monitoring short and medium span bridges (González, 2010).

An approach to B-WIM proposed by Sekiya et. al. (2017) uses derived displacement responses from bridge accelerations to estimate axle weights (Sekiya, Kubota, & Miki, 2017). In this process, the bridge initial conditions are assumed for integration of the acceleration response which is a source of inaccuracy. A new B-WIM method is proposed in this paper which uses bridge midspan accelerations directly to calculate vehicle weights and detect damage in the bridge using statistics of traffic data. The advantage of this method is that it requires installation of only one accelerometer at midspan and the axle detectors.

The aim of this paper is to simulate and numerically test an acceleration-based B-WIM system for effective BHM. Since, the statistical properties of traffic (for example, the most frequent GVWs of 3-axle trucks) tend to be consistent; a statistical approach is applied on the inferred B-WIM results. In this paper, histograms of inferred B-WIM results for different bridge damage percentages are compared with the result histogram for the healthy bridge. Damage is represented as a loss of stiffness in the bridge deck (Sinha, Friswell, & Edwards, 2002) and manifests itself as an apparent increase in gross weights . Change in the statistical properties of the inferred GVWs is taken as an indication of a change in the bridge condition.

2. B-WIM System Using Accelerations

Bridge dynamics responses, like acceleration, are more complex as compared to the static responses. Development of the B-WIM system requires the bridge responses to be scalable and to obey the principle of superposition. In this section, bridge acceleration responses are studied to see if they follow the principles required for the B-WIM system.

2.1 Feasibility of the B-WIM System

To use the bridge acceleration response in a B-WIM system, the relationship between bridge accelerations and vehicle weights has to be considered. The possibility of the scaling principle of the response depends on the linearity of this relationship. Acceleration responses are simulated here numerically using a single quarter-car vehicle model crossing a simply supported beam. Axle weights ranging from 5t to 30t are used to see how the response changes with increasing weight of the axle. The velocity of all these vehicles is taken as 80 km/h and the initial conditions of the bridge are kept constant for the simulations. The bridge mid-span accelerations are plotted in the time domain for comparison which can be seen in Figure 1. Vehicle mass affects the first natural frequency of the system. However, the vehicle is light relative to the bridge self-weight so the influence is small, and the signals are all similar in shape. The first positive peak of the response, which has the highest amplitude, is considered in more detail. Figure 2 shows the change of amplitude with axle weight, normalized with respect to the 5t axle peak. The regression of this relationship is found to be fairly linear, with a coefficient of determination of 99%. This suggests that the acceleration responses, like strain responses, are a linear function of axle weight.

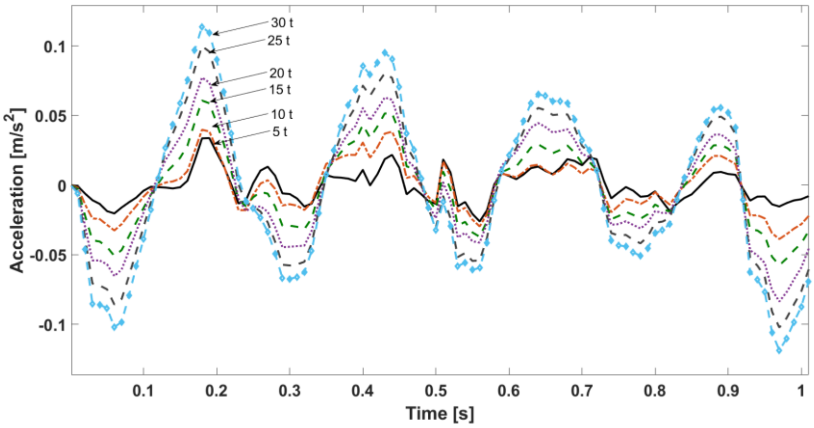


Figure 1 – Mid-span bridge acceleration responses to single quarter-car with a range weights.

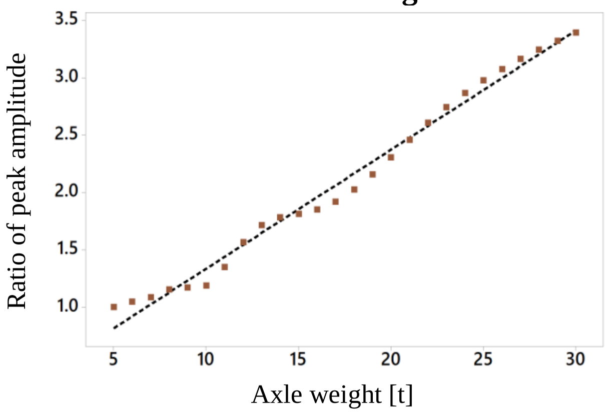


Figure 2 – Ratio of amplitudes to that of 5t axle response for first positive peak

For the case of multi-axle vehicles, the bridge response must satisfy the principle of superposition for a B-WIM system, i.e., the response to many axles must equal the sum of responses to each individual axle. To test this, the bridge acceleration response to a pair of quarter-cars and the sum of the responses to two individual quarter-cars, are plotted in Figure 3. This figure shows the small difference between the combined response and the sum of the individual responses, suggesting that the bridge accelerations roughly follow the principle of superposition.

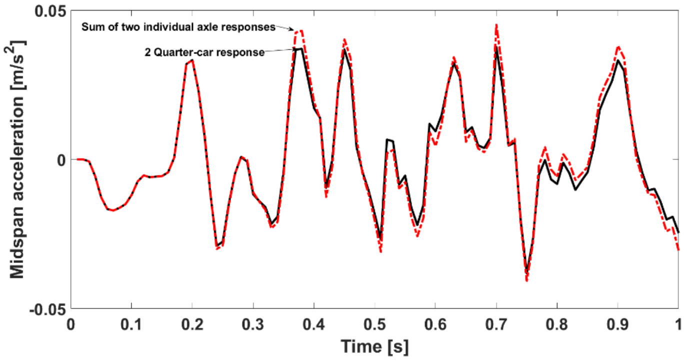


Figure 3 – Simulted acceleration responses to two quarter-cars and sum of two individual axles responses

Since the bridge acceleration responses are not only linear but also superimposable, it is possible to develop an acceleration-based B-WIM system. The theoretical acceleration response (R^{th}) can be calculated as a sum of products of axle-weights and the corresponding influence line ordinates – see Equation 1. To calculate the time step difference due to axle spacing; number of axles, axle spacings and vehicle velocity are required.

$$R^{th}(\mathrm{t}) = W_1 I(t) + W_2 I(t - t_{12}) + W_3 I(t - t_{13}) + \cdots \quad (1)$$

where:

W_i = i[th] axle weight
$I(t)$ = Influence line ordinate corresponding to axle 1 at time step t
t_{1j} = time step difference due to axle spacing between arrival of axle 1 and axle j

In this paper, a two quarter-cars vehicle model (Figure 4) is simulated for the acceleration-based B-WIM analysis. 'Measured' mid-span bridge acceleration responses (R^m) and the corresponding theoretical responses are calculated (see Figure 5). Equation 2 shows the Moses' objective function for the B-WIM analysis (Moses, 1979).

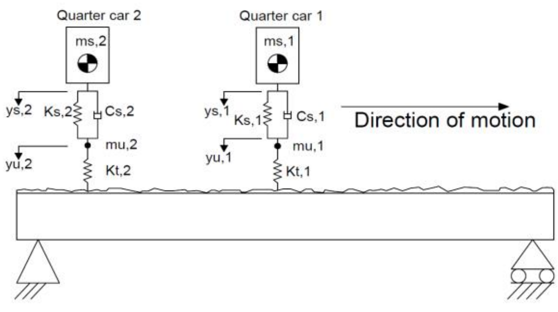


Figure 4 – Two quarter-cars vehicle model

$$O = \sum_{t=1}^{n}(R^{m}(t) - R^{th}(t))^2 \quad (2)$$

where:

t = time step
n = total number of time steps during passage of the vehicle

The inferred axle weights are those for which the sum of squared differences between the measured and theoretical responses (*O*) is minimum. This minimum is calculated for each axle by setting the partial derivative of *O* with respect to each axle weight to zero for each time step:

$$\frac{\partial O}{\partial W_j} = 0, \quad j = 1,2,3 \ldots\ldots n_{axle} \quad (3)$$

where n_{axle} is the number of vehicle axle.

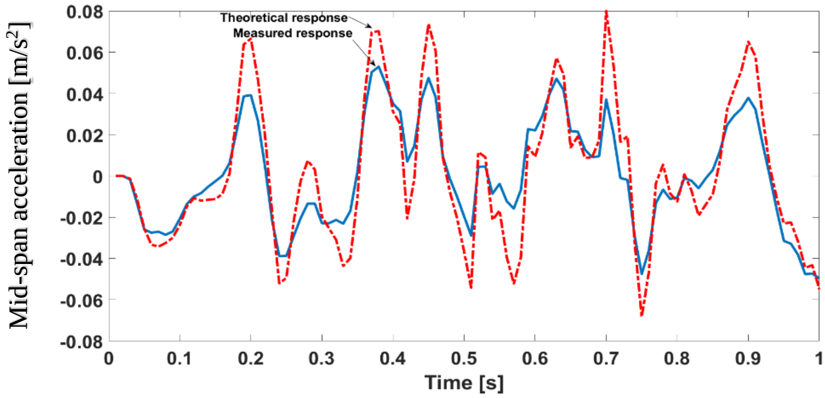


Figure 5 – The simulated measured and the theoretical acceleration responses

2.2 Numerical Model

In this study, a pair of quarter-cars model passing over a simply supported beam has been programmed in MATLAB. The vehicle model contains 4 degrees of freedom (DOFs) which consist of sprung mass bounce translation and axle hop translation for each quarter-car. The properties of the vehicle are given in Table 1. The weight of each axle, vehicle velocity and axle spacing are generated randomly using Monte Carlo function for each run of the simulation.

The bridge has been simulated as 1D finite element model of a simply supported beam. An approach length of 100 m is included to ensure that the DOFs are in equilibrium when the vehicle arrives on the simulated bridge. The bridge properties are shown in Table 2.

The Vehicle Bridge Interaction analysis is carried out using the Wilson-Theta method which calculates beam displacement, velocity and acceleration at each vehicle location/time step. A road profile, generated randomly according to the ISO standard, is added to the model with a class ‘A’ roughness (Tyan, Hong, Tu, & Jeng, 2009). Random pre-existing vibrations are added to the beam model so that the initial conditions are represented realistically.

For the case of a damaged bridge (Figure 6), damage is represented as a loss of stiffness with different percentages in a central element (10^{th}) of the beam. For this model, a triangular loss of stiffness is assumed that extends 1.5 times the beam depth on either side of the crack (Sinha et al., 2002). Cracks representing depth losses of 5%, 10%, 15%, 20%, 25% and 30% are simulated.

Table 1 – Properties of a quarter-car

Quarter-Car Property	Notation	Value
Unsprung mass	m_u	750 kg
Tyre stiffness	K_t	3.5×10^6 N/m
Suspension Stiffness	K_s	7.5×10^5 N/m
Suspension Damping	C_s	10^3 Ns/m

Table 2 – Properties of bridge

Bridge Property	Notation	Value
Length of Bridge	L	20 m
Number of elements	N	20
Young's Modulus	E	3.5×10^{10} N/m^2
2nd moment of area	I	0.75 m^4
Mass per unit length	μ	37500 kg/m
Damping	ξ	3%
1st natural frequency	f_1	4.2 Hz
Scan frequency	f_s	100 Hz

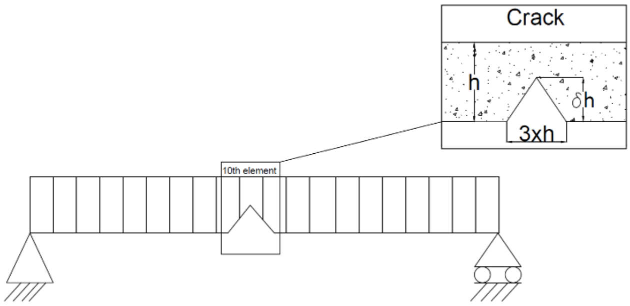


Figure 6 – Model of crack (bridge damage)

2.3 Accuracy of the B-WIM System

The accuracy of the B-WIM system is assessed by comparing the actual GVWs used to generate the acceleration signals and the inferred GVWs. The B-WIM system accuracy is then classified using the "COST 323" classification model (Jacob, O'Brien, & Newton, 2000). It is acknowledged that true accuracy is likely to be considerably less than that calculated in a numerical study of this type. In this study, 500 pairs of quarter-cars are simulated on a simply supported bridge model with randomly chosen axle weights, velocities and axle spacings. Using a pair of quarter-cars instead of a half-car simplifies the problem as it prevents vehicle rocking and the resulting interaction between axles. The acceleration-based B-WIM analysis is carried out on the calculated responses and axle weights for each vehicle are inferred.

Histograms of actual GVWs used to simulate the acceleration responses and the inferred GVWs, are plotted in Figure 7. The histogram of the inferred GVWs is shifted towards the left showing that the acceleration-based B-WIM system is inaccurate, and it significantly underestimates the GVWs. The normal distribution curve fits to the histograms (also shown in Figure 7) show that the mean of the inferred GVWs has decreased as well as the standard deviation. This may be due to the fact that destructive interference between the vibration signals caused by each axle are reducing the amplitude of the measured response in a way that the linear assumption, used in the B-WIM equation, does not allow for. Evidence of this can be seen in Figure 5 where the amplitudes in the 'measured' response are consistently less than the theoretical equivalent.

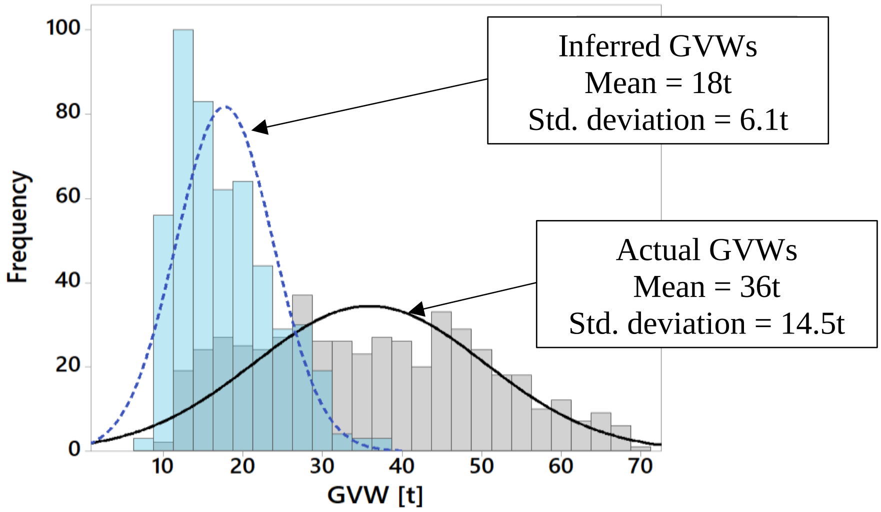


Figure 7 – Histograms of actual simulated GVWs and the inferred GVWs

3. Bridge Health Monitoring Using Acceleration-Based B-WIM System

Bridges generally experience a loss of stiffness due to cracks in the deck or loss of reinforcement area (Sinha et al., 2002). As mentioned earlier, bridge accelerations are sensitive to damage at any location. Therefore, the acceleration-based B-WIM system is proposed for bridge damage detection and health monitoring. Figure 8 shows the effect of damage on the mid-span bridge acceleration. The amplitude of the acceleration response to a 20t vehicle using a damaged bridge is generally greater than the amplitude using the same vehicle on a healthy bridge. The reason for this increase is an increase in the deck flexibility. As a result, the difference between the theoretical and the measured acceleration responses changes.

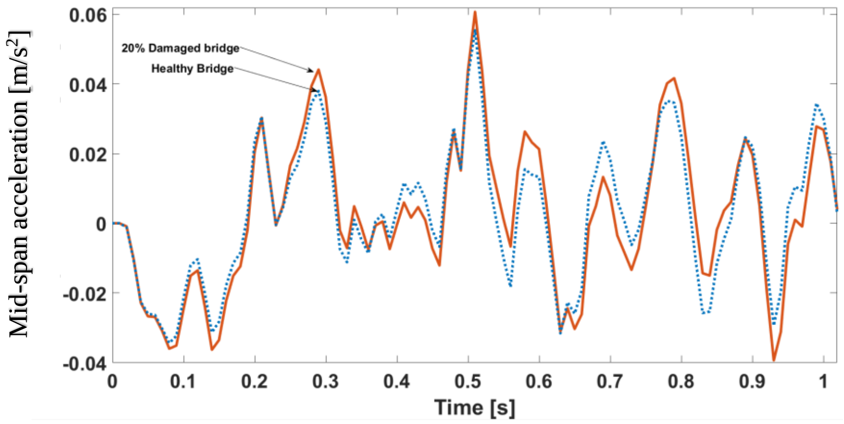


Figure 8 – Mid-span acceleration responses in healthy and damaged bridge conditions

The change of acceleration response amplitude causes the change in the B-WIM results. The statistical properties of the inferred GVWs change with the change in bridge condition. Figure 9 shows the normal distribution fits of inferred GVWs histograms using the bridge with various damage percentages. This analysis used data from the same 500 trucks in simulation for each damage percentage.

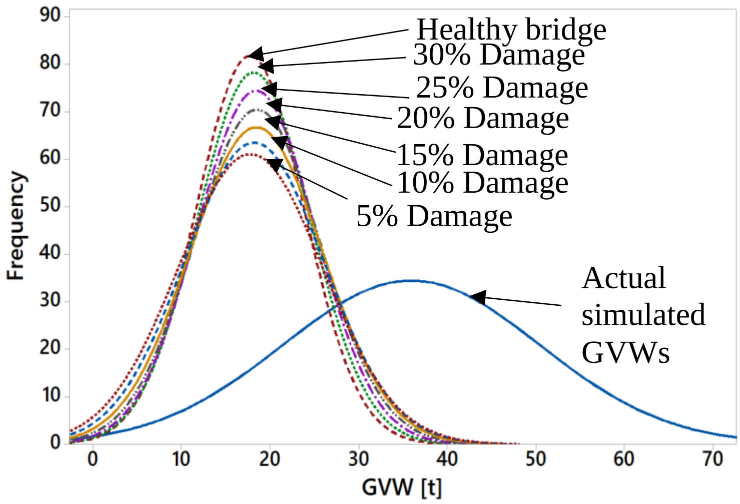


Figure 9 – Normal distribution fits of actual and inferred GVWs with various bridge health conditions

4. Results and Discussion

As mentioned earlier, an acceleration-based B-WIM system can be developed if axles configuration and vehicle velocity are known. The mean accuracy of the acceleration-based B-WIM system using 500 simulated pairs of quarter-cars is calculated to be -49% which is clearly not effective for truck weighing. The acceleration-based B-WIM system is classified in Class E according to the "COST 323" classification standard (Jacob et al., 2000). The histograms in Figure 5 also indicate that the acceleration-based B-WIM system underestimates the GVWs by shifting the inferred GVW histogram to the left. The role of the road profile is a key factor in the vehicle and bridge acceleration responses. Figure 10 shows the effect of profile on the acceleration responses. The theoretical and measured responses for a perfectly smooth profile do not show any difference (Figure 10(a)) while with a road profile, they differ significantly (Figure 10(b)). The reason for the difference is the second-axle interaction – the first axle causes the bridge to vibrate so the second axle is excited by a road profile that is contaminated by bridge vibration. Similarly, the second axle also contaminates the excitation of the first axle.

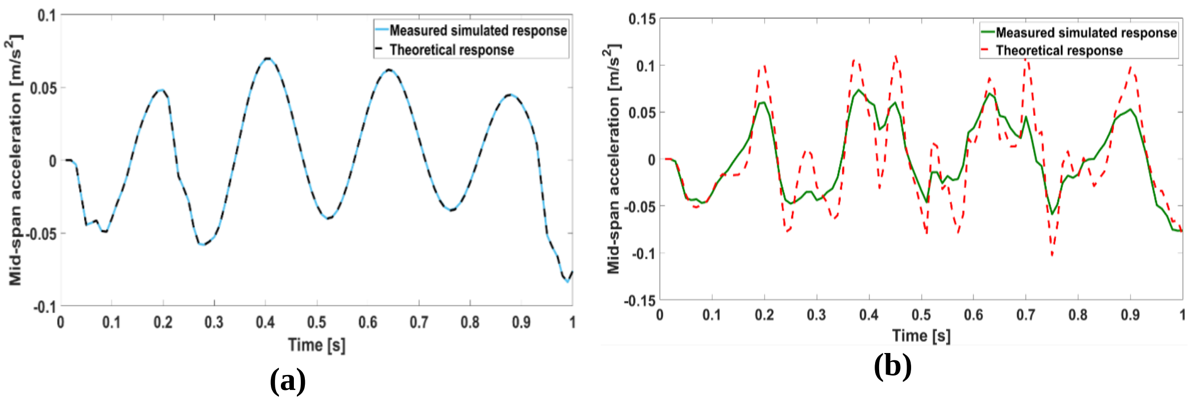
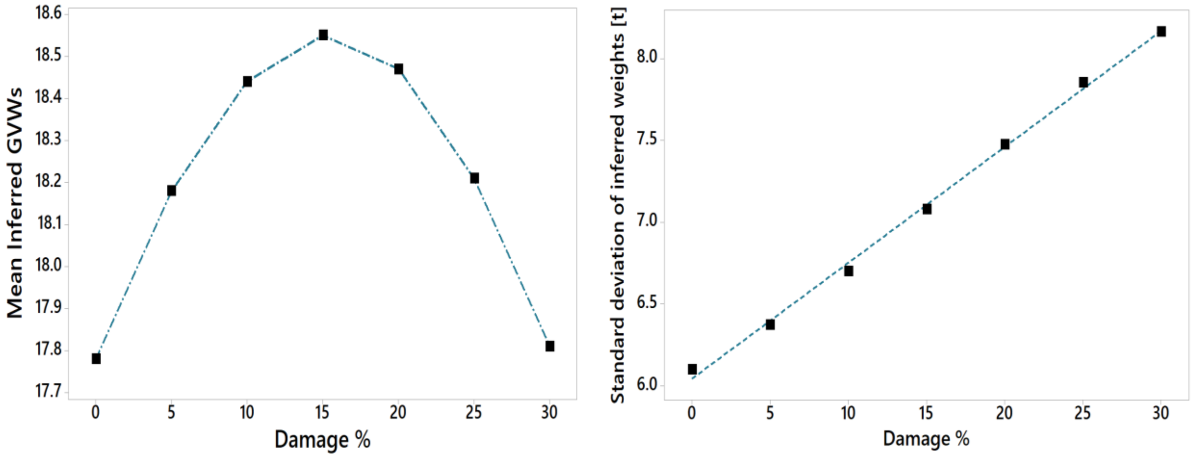


Figure 10 – Theoretical and measured acceleration responses: (a) For perfectly smooth profile; (b) For Class A road profile

Although the acceleration-based B-WIM system is not very accurate for inferring GVWs, but Figure 8 shows that the system demonstrates significant and consistent variation in the statistical properties of inferred weights with damage. The variation of the means and the standard deviations of the inferred GVWs are shown in Figure 11. The mean inferred GVW increases initially to reach a maximum at 15% bridge damage, then decreases with further increase in damage percentage, showing that the measured acceleration response. The relationship between the standard deviation and the damage percentage is fairly linear, and for that reason, it has a potential for bridge health monitoring. This relationship makes it possible to measure the damage percentage of bridge if healthy bridge traffic data, using the B-WIM system, is available.



(a) **(b)**

Figure 5 – Influence of damage on statistical properties of inferred GVW: (a) Mean; (b) Standard deviation

5. Conclusion

This paper develops a new BHM approach using acceleration-based B-WIM system. The B-WIM system is found to be feasible as a means of monitoring bridge health and the change in the B-WIM results with bridge damage is significant. The accuracy of the inferred weights using the acceleration-based B-WIM system is poor. However, statistical analysis of the B-WIM results with various bridge damage percentages is found to be quite effective for bridge health monitoring. The relationship between the bridge damage percentage and the standard deviation of the inferred weights is fairly linear. In the analysis, the bridge is modelled with pre-existing vibrations and the role of road profile in changing the B-WIM results is investigated to understand the results. The change in the statistical properties of the B-WIM results make it possible to quantify the extent of the bridge damage. It is also noted that road profile affects the bridge acceleration response significantly causing inaccuracies in the B-WIM system, for which, further study is required.

6. Acknowledgement

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FATIGUE ASSESSMENT OF NORMANDY BRIDGE UNDER TRAFFIC LOADING

  

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Abstract
The local authorities asked in 2017 the concessionaire of the bridge of Normandy (CCISE), a 856 span length cable stayed bridge, to study the feasibility opening it to abnormal loads up to 120 t. The CCISE asked the advice of the bridge designer, M. Virlogeux, and to IFSTTAR, to measure the current traffic loads on the bridge, in operation since 1994, to assess the fatigue lifetime under this real traffic loads, and to estimate the potential lifetime reduction if the abnormal loads up to 120 t were allowed.
IFSTTAR and Cerema installed a bridge WIM system (SiWIM) in July 2017 on the bridge to measure the traffic loads over more than 7 months. These data allowed assessing the expected lifetimes of the most sensitive details of the orthotropic steel deck. These lifetimes were compared with those obtained under 3 other traffics recorded on other French motorways. Then the fatigue damage induced by 4 conventional abnormal loads (2 cranes of 96 and 108 t, and to vehicles C1 and C2 of 94 and 120 t) was calculated. Finally, the lifetime reduction if each of these 4 abnormal loads cross the bridge twice a day was assessed.

Keywords: Traffic load, abnormal load, Weigh-in-Motion (WIM), Bridge WIM, orthotropic deck, fatigue, lifetime.

Résumé
Les autorités locales ont demandé en 2017 au concessionnaire du pont de Normandie (CCISE), ouvrage haubané de 856 m de portée, d'étudier la possibilité d'ouvrir le pont à des transports exceptionnels jusqu'à 120 t. La CCISE a demandé l'avis du concepteur de l'ouvrage, M. Virlogeux, et à l'IFSTTAR de mesurer les charges de trafic sur le pont en service depuis 1994, d'estimer la durée de vie en fatigue et sa réduction potentielle si les convois jusqu'à 120 t étaient autorisés.
L'IFSTTAR et le Cerema ont installé un système de pesage par pont instrumenté (SiWIM) en juillet 2017 pour mesurer les charges de trafic pendant plus de 7 mois. Ces données ont permis de calculer les durées de vie des détails les plus sensibles du platelage de la dalle orthotrope. Ces durées de vie ont été comparées à celles obtenues avec 3 autres trafics autoroutiers français. Ensuite le dommage en fatigue induit par 4 convois exceptionnels (2 grues de 96 et 108 t et 2 convois conventionnels C1 et C2 de 94 et 120 t) a été calculé. Finalement la réduction de durée de vie du pont a été estimée si chacun de ces 4 convois passaient 2 fois par jour.

Mots-clés: charges de trafic, charges exceptionnelles, pesage en marche (WIM), pesage apr pont instrumenté, dalle orthotrope, fatigue, durée de vie.

1. Bridge Description and Context

The bridge of Normandy crosses the Seine river, near to its estuary, between Le Havre, a main French harbor, and Honfleur (Figure 1). It carries the motorway A29, called "Estuaries' motorway" linking Amiens and the north of France and Channel tunnel to the west and south-west. The bridge built in 1991-93 opened in 1994. It is the third bridge crossing the Seine river downstream of Rouen, an inland maritime harbor located 100 km away from the sea. The two other bridges between Rouen and the sea are the suspended bridge of Tancarville (1959, main span of 608 m, a Robinson steel deck, total length 1420 m), carrying the motorway A131 (Le Havre to Paris), and the cable stayed bridge of Brotonne (1977, main span 320 m, total length 1278 m, pre-stressed concrete). Cracking affects this last bridge and thus it has some gross vehicle weight limitation.

The bridge of Normandy is 2143 m long, with approaching viaducts in concrete and a main cable stayed span of 856 m in length (624 m as a steel orthotropic deck), 59 m above the river level. The deck is 23.6 m in width and carries 4 traffic lanes, two cycling lanes and two pedestrian paths. The two pylons are 215 m in height. 184 cables support the deck. It is a toll bridge operated by the Chamber of Commerce and Industry of the Seine Estuary (CCISE). The concession lasts until 2027.

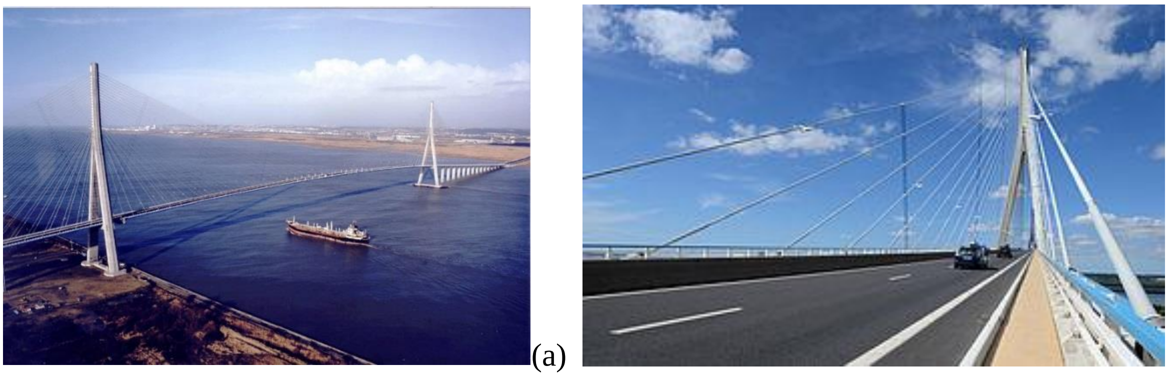

(a) (b)

Figure 1 – Bridge of Normandy, (a) aerial view from the south, (b) view of the deck.

Until now none of these three bridges are open for abnormal loads above 48 t (category 1), and the abnormal loads of categories 2 (up to 72 t) and 3 (> 72 t) have to cross the Seine river in the city of Rouen, which causes disturbances and induce long detour for most of them. Therefore, the prefect of Seine-Maritime wanted to open the bridge of Normandy to abnormal loads up to 120 t, near the harbor of Le Havre. The concessionaire (CCSIE) which must return the bridge in perfect conditions to the State in 2027, asked to its designer, Michel Virlogeux, to advise about the risk in fatigue of the steel deck. An initial study was carried out by the LCPC in 1995 (Carracilli and Jacob, 1995), using measured influence lines and some traffic data recorded on other motorways, such as on the bridge of Tancarville. In May 2017, M. Virlogeux and the CCISE appointed the IFSTTAR to carry a study on the effect of the current traffic and abnormal loads on the fatigue of the steel orthotropic deck. A first assessment was made by the consultancy Quadric, applying the Eurocode 1991-2 fatigue load model (CEN, 2003), but because of inappropriate load application conditions and a very conservative load model, the computed lifetimes were extremely low (app. 1 year!) and very doubtful for a 22 year bridge.

IFSTTAR proposed first to measure the traffic loads on the bridge, using the SiWIM, a bridge WIM system manufactured by the Slovenian company Cestel. Then using the influence lines measured in 1995 the fatigue lifetimes were calculated for the most sensitive details, and compared to the results of the initial study in 1995 for one detail. Finally, the effect of 4 abnormal loads were calculated, and the lifetime reduction estimated with a quite conservative scenario of abnormal load crossings.

2. Details sensitive to Fatigue and Influence Lines

2.1 Details sensitive to fatigue and deck instrumentation

The steel part of the Normandy bridge is made of 32 segments of 19.65 m in length and 3.05 m in height, each being supported by two cables, one on each side. The segments are boxes with longitudinal stiffeners under the upper plate and above the lower plate, and cross beams spaced by 3.93 m. The longitudinal stiffeners are 0.30 m in with, in height and spacing (i.e. 0.60 m between the vertical axis of 2 adjacent stiffeners). The upper plate is 14 mm thick under the slow lanes and 12 mm thick under the other lanes, and the stiffeners thicknesses are resp. 6 and 7 mm. However, a cycling lane was added after the bridge opening, which shifted the traffic lanes to the left, and the thickness changes between the stiffeners noted J6 and J11. Figure 2 shows the cross section, the traffic lanes layout and the strain gauges installed in 1995. The most sensitive details in fatigue are the welds between the upper deck plate and the longitudinal stiffeners, with cracking risk either in the upper plate just outside the stiffener (traction stresses under transverse bending), or in the stiffeners' flanges just below the weld. A series of strain gauges were installed in 1995 to measure the influence lines and assess the stress cycles under traffic loads (Figure 2).

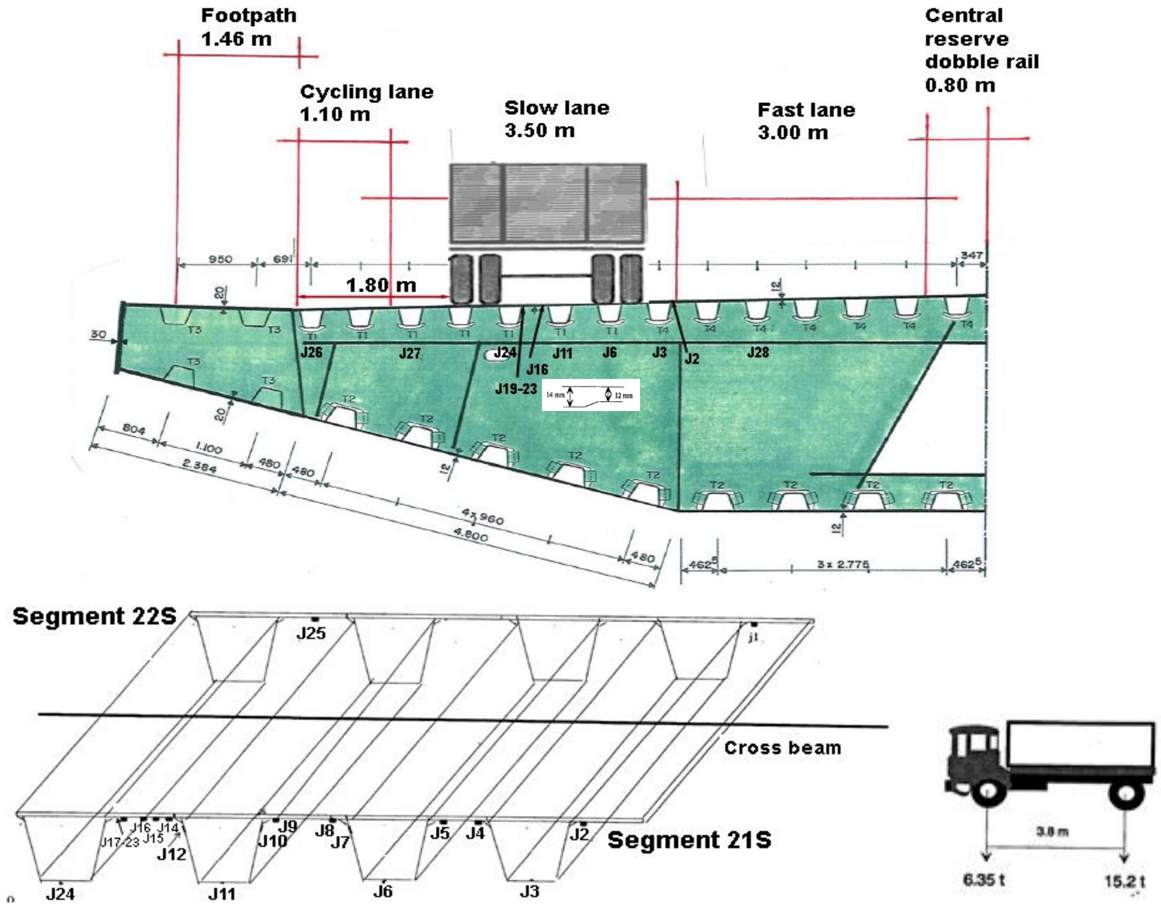


Figure 2 – Bridge of Normandy, transverse cross section, stain gauges and test truck (1995)

Three sets of strain gauges (J) were mounted mainly under the slow traffic lane:

- under the stiffeners bottom face at mid-span between two cross beams, to measure the longitudinal bending moment stresses (no fatigue effects): J3, 6, 11, 24, 25, 26, 27 and 28;
- under the upper deck plate to measure the transverse bending stresses: J2, 4, 5, 8, 9, 14, 15, 16 and a chain J17-23;
- outside the stiffeners' flanges just below the longitudinal welding: J7, 10 and 12.

2.2 Influence Lines

The influence lines corresponding to the stresses recorded by each strain gauge were measured in 1995 using a 2-axle rigid test truck (6.35 – 15.21 t) shown in Figure 2. The 2nd axle, supported by two twin wheels, was used to determine the influence lines. Figure 2 shows the transverse location of the truck in the slow lane. The influence lines of the 3 most sensitive details (J7, 10 and 12 for the stiffener flanges, and J8, 9 and 23 for the upper plate of the deck) are given in Figure 3, and used in the fatigue analysis. Most of these details are located near the left wheel path of the test truck. The gauges J7 and 8 are located under the 12 mm thick plate, while the gauges 9, 10, 12 and 23 are under the 14 mm thick plate.

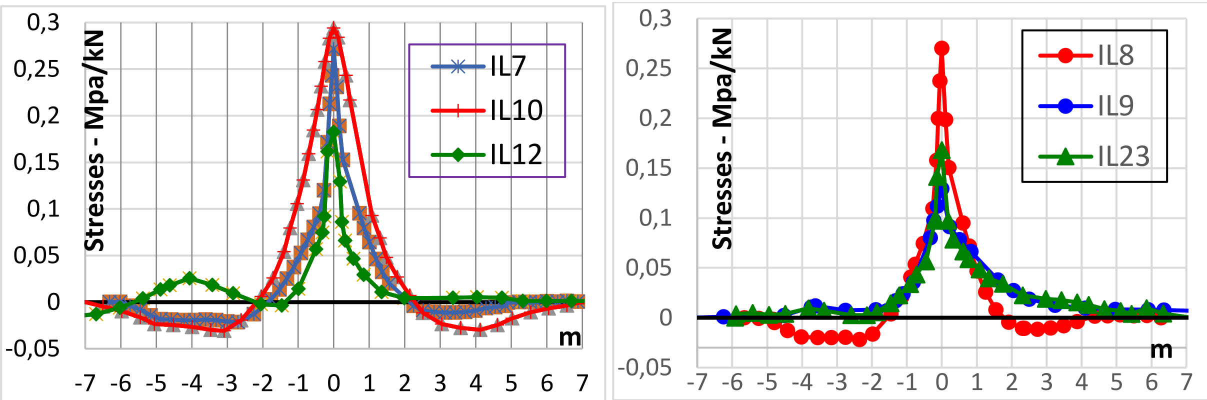
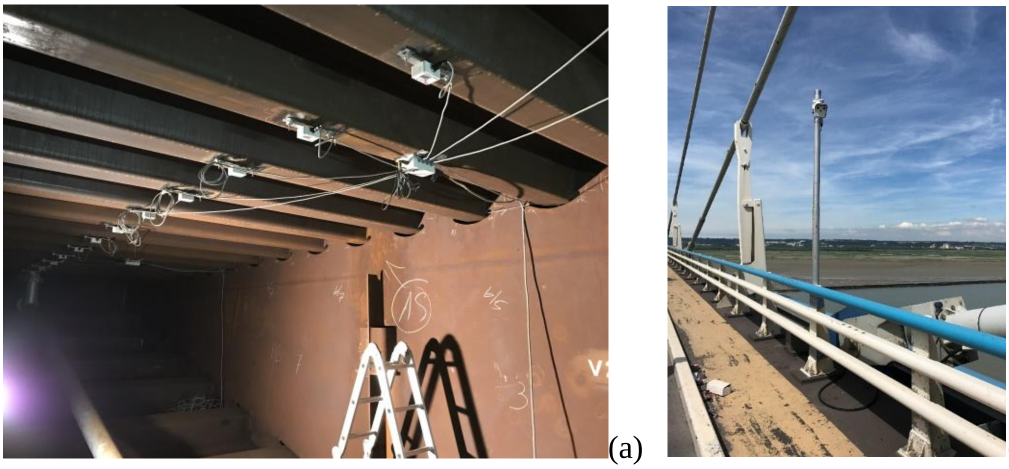


Figure 3 – Influence lines: stiffener flange (left), upper plate/deck (right)

3. Traffic loads

3.1 Measurement of the Normandy Bridge Loading by B-WIM

Early July 2017, IFSTTAR and Cerema installed the bridge WIM (B-WIM) system SiWIM, manufactured by the Slovenian company Cestel and lent for a research project on direct enforcement by WIM. The SiWIM was installed under the traffic lanes in the south-north direction in the segment 21, just north of the bridge mid main span. This section was chosen because the slope is almost negligible and the distance to the tollgate (located at the north end of the bridge) is 2 km, which allows capturing the overloaded trucks during enforcement sessions. 14 extensometers were fixed under the lower face of the longitudinal stiffeners at mid-span between two cross beams, 7 under each traffic lanes (Figure 4a). They measure the strain induced by the bending of these stiffeners while wheels are crossing this bridge section, from which the axle and vehicle weights are derived (Dempsey et al. 1998, 2000). Four more extensometers were installed beyond the upstream and downstream crossbeams to measure the vehicle velocities and to launch the strain record when a vehicle is approaching. A camera was mounted on a mast along the right traffic lane on the bridge deck, to record the truck pictures and license plates if overloaded (Figure 4b).



(a) (b)

Figure 4 – SiWIM in the Normandy bridge: (a) extensometers under the longitudinal stiffeners in the box, (b) camera on the bridge deck

The system was calibrated with 25 runs of a 5-axle articulated truck, type T2S3. Its static gross weight was 42.39 t, and the axle loads were 5.77 t, 7.9 t and 28.72 t (tridem). 4 runs were eliminated because of doubtful values and large gross weight errors. The accuracy of the SiWIM, assessed using the COST323 Specs (Jacob et al., 2002)) was not good as shown in Table 1, above all for the single axles, mainly because of a very high scattering of the axle loads, not fully explained. An accuracy check was done on August 2, with 36 vehicles from the traffic flow, weighed in static after the tollgate on an approved axle scale. The SiWIM accuracy was in class E(35) for the gross weights and groups of axles, and in E(50) for the single axles. For the 5 axle-articulated (T2S3), and after recalibration, the accuracy was E(30), E(30) and E(40) for the 3 criteria. Again, the axle loads are highly scattered, which is not fully explained. The accuracy on Millau bridge, another orthotropic deck cable stayed bridge, instrumented in 2009 was better (Jacob et al., 2010), and even improved in 2016 after the installation of a new SiWIM, almost in class B(10) (Schmidt et al., 2016). In addition, here it was necessary to require to ZAG in Slovenia to revise twice the SiWIM parameter settings, because initially many aberrant values were generated, e.g. axles with no load or abnormal heavy loads, etc.

Table 1 – Accuracy of the SiWIM (Calibration test, conditions R1/I), vs COST323.

	n	m (%)	s (%)	δ_{min} (%)	Class
Gross weight	21	0.24	6.33	18.0	D(25)
Group of axles	63	-2.61	4.04	12.9	C(15)
Single axles	42	5.35	14.76	42.9	E(50)

The SiWIM recorded the traffic across the bridge from July 2017 until January 2018 for this study, and even more, until May 2018 after it. 237,584 truck above 3.5 t were recorded over 7 months, and 224,354 (94.4%) were kept after cleaning the file and removing the aberrant vehicles. 61% of the trucks are 5-axle, then 18% are 4-axle and 13% 2-axle. There are 5% of 3-axle and 3% of more than 5 axles vehicles. Figure 5 shows the heavy traffic increase since the opening of the bridge, compared to the heavy traffic on the Tancarville bridge, and the gross weight distribution.

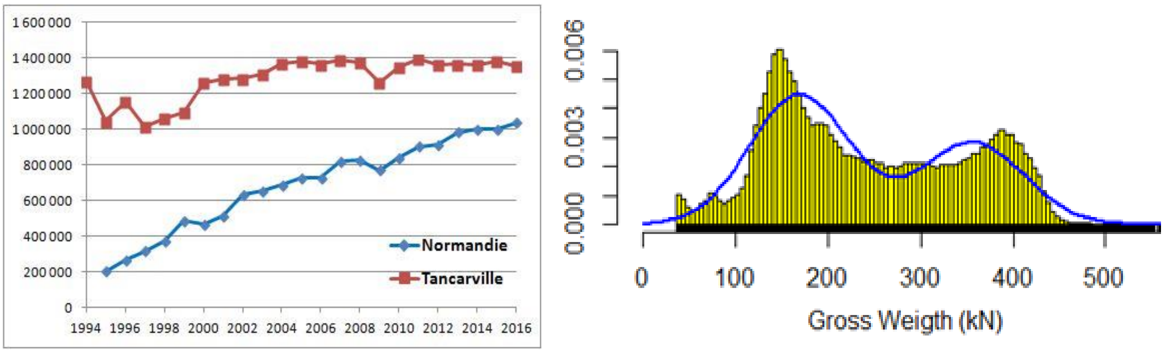


Figure 5 – Heavy traffic on the Normandy bridge: (left) truck flow evolution 1994-2016, (right) gross weight distribution (> 3.5 t)

3.2 Traffic applied for the Fatigue Assessment of Normandy Bridge

The traffic measured on the Normandy over 189 days is conservative to assess the fatigue of the bridge details over the past 24 years of operation, because of the continuous increase of the traffic flow (Figure 5). However, in the future the traffic may still increase, in both volume and loads. Therefore, it is useful to calculate the lifetimes of the most critical details if exposed to other traffics. We used 3 other traffics recorded by the National WIM network on two other motorways (A20 and A9) and a main highway (RN4). Table 2 reports the relevant statistics of these traffics.

Table 2 – Traffics of French motorways and highways for fatigue assessment.

Site	Dates	Nb days	Nb trucks	Mean flow trucks/day	Proportion . 2nd mode	Median 2nd mode (kN)	St. Dev. 2nd mode (kN)
Normandy (A29)	7/17-1/18	189	224354	1187	40%	350	50
Massay (A20)	2015	362	498269	1376	20%	384	27
Maulan (RN4)	2015	353	755757	2141	28%	383	30
Fabrègues (A9)	1-6/2015	189	901231	4768	40%	371	26

The traffic measured on the A20 in the center of France (Vierzon to Limoges) has the closest statistics to the A29 traffic on the Normandy bridge, with slightly higher loads in the 2nd mode of the gross vehicle weights, but a lower proportion of trucks in it. The traffic on the RN4 (highway Paris-Nancy) is the second closest one, but with a 80% higher volume of trucks. The traffic of the A9 motorway near Montpellier (Lyon to Barcelona) is one of the heaviest in France and much ore aggressive than the A29. It gives an upper bound of the fatigue damage, but much too conservative. All these traffic were measured over 6 to 12 months in 2015, with several hundreds of thousends of trucks.

3.3 Abnormal Loads

The four abnormal loads considered for the fatigue study, are representative of the potential abnormal loads, which could cross the bridge of Normandy if allowed in the future. Two cranes (G1 and G2) and two standard abnormal loads (C1 and C2) are used (Figure 6). All the crane axles have a 12 t load, i.e. G1 weighs 8 x 12 = 96 t, and G2 weighs 9 x 12 = 108 t. The axle spacings are for each crane:

- G1: 1.50 - 1.55 - 2.00 – 1.50 – 2.39 – 1.50 – 2.49 m;
- G2 : 1.65 - 1.65 - 2.00 – 1.50 – 2.485 – 1.50 – 2.615 – 1.50 m ;
- and all the tires are 14-R25, 0.356 m in width (2 tires per axle).

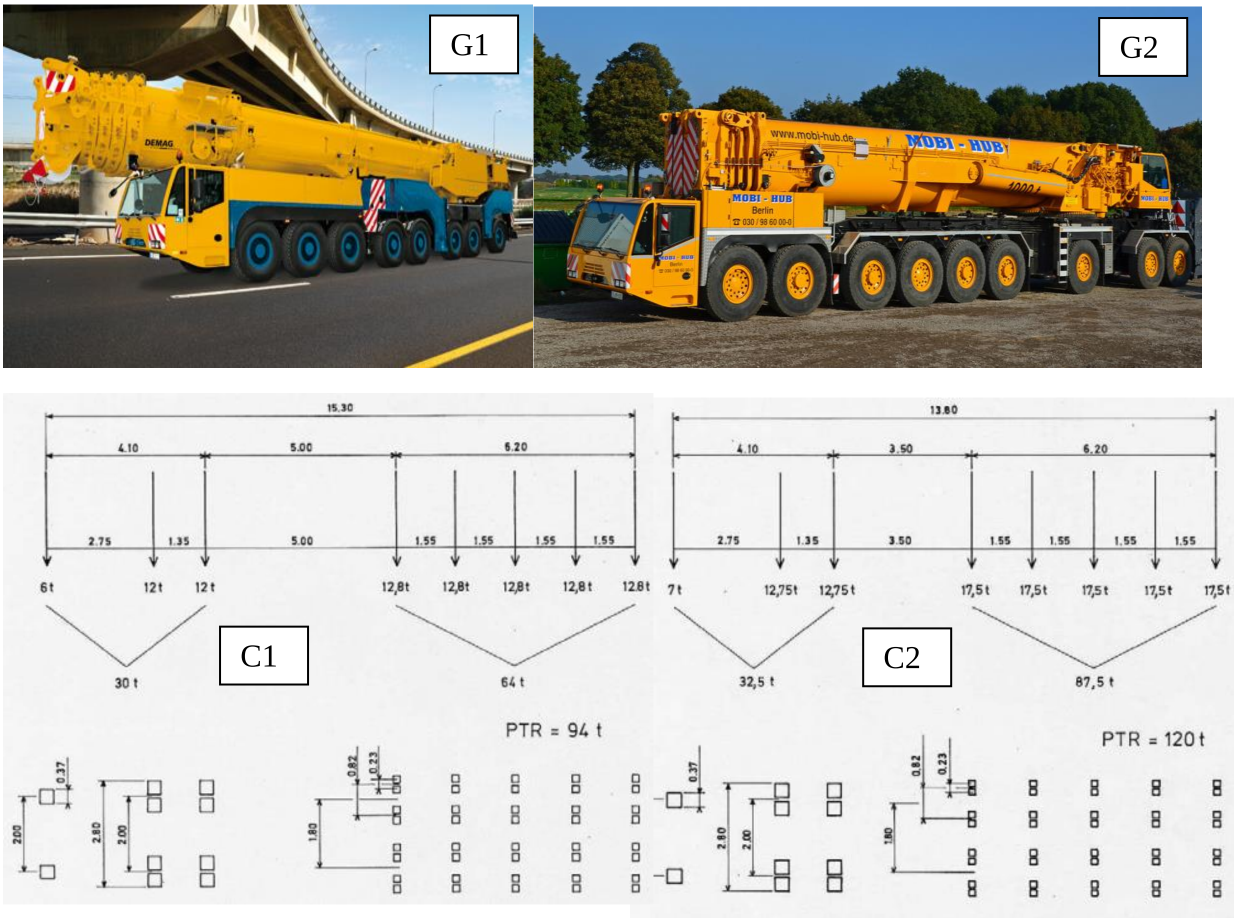


Figure 6 – Abnormal loads: (G1) (G2) cranes 98 t - 108 t, (C1) (C2) vehicles 94 t - 120 t

The vehicles C1 and C2 have the same geometry. They consist of a single front axle of 6 or 7 t with single tires, a tandem axle (2x12 t or 2x12,75 t) with dual tires, and a series of 5 axles, spaced by 1.55 m, loaded at 12.8 t or 17.5 t, with 4 twin tires each (i.e. 8 wheels per axle). The tires of the 3 first axles are 0.37 m in width.

The future number of abnormal load crossings are assumed as 2 crossings of each (G1, G2, C1 and C2) per day and direction but the week-ends, i.e. 600 crossing of each per year. This assumption is conservative, in order to make a safe estimation of the expected lifetimes.

4. Fatigue Assessment

4.1 Methodology

The rain-flow histograms of the stress variations under the four traffics were calculated using the CASTOR-POLLUX software (Schmidt and Jacob, 2010), and the fatigue lifetimes derived with the Miner's law, assuming a stationary traffic all along the lifetime, and with the fatigue classes 71 and 50. The traffic stationarity is quite conservative according to the low traffic on the bridge during the first years of operation, but a future traffic flow or loads increase may compensate that. The details are in class 70 for good welds according to the Eurocode 1993-2 (Steel bridges). However, the class 50 corresponds to potential defective welds.

For the abnormal loads, each crossing induces a limited number of stress cycles. E.g. the two cranes induce each 4 cycles, G1: 1 tridem + 2 tandem + 1 single axle, G2: 1 tridem + 3 tandem.

Because of the short lengths of the influence lines (local effects), when the spacing between two axles exceeds 2 m, two independent cycles may be considered. Reversely, according to the influence line shape, each group of axles (internal spacing below 1.65 m) induces a single stress cycle. Similarly, the C1 and C2 vehicles induce each 3 cycles, for the single axle, the tandem and the group of 5 axles. However, the cycle due to the front axle never exceed the truncation threshold of the fatigue S-N curves in the classes 50 and 71, resp. 20.2 and 28.7 MPa, and thus are ignored. Table 3 gives all the stress cycles induced by these abnormal vehicles.

Table 3 – Stress cycles induced by each abnormal vehicle on the 6 influence lines.

Influence line	Stress cycles (rain-flow) in MPa			
	Crane G1	Crane G2	Vehicle C1	Vehicle C2
IL J7	36.5 – 2 x 34.8 – 32.0	34.9 – 3 x 34.8	36.6 – 39.1	38.9 – 53.5
IL J10	45.3 – 2 x 40.2 – 34.6	42.4 – 3 x 40.2	42.7 – 48.2	45.4 – 66.0
IL J12	22.9 – 2 x 22.5 – 21.5	21.9 – 3 x 22.5	23.1 – 24.5	24.5 – 33.6
IL J8	33.0 – 2 x 32.8 – 31.8	32.3 – 3 x 32.8	34.7 – 35.7	36.9 – 48.7
IL J9	21.7 – 2 x 20.1 – 15.2	20.8 – 3 x 20.1	22.4 – 23.2	23.8 – 31.8
IL J23	25.8 – 2 x 24.2 – 19.8	25.2 – 3 x 24.2	24.9 – 27.8	26.4 – 38.1

4.2 Lifetime Calculation under real Traffics

Table 4 gives the lifetimes calculated for the 6 influence lines, IL J7, 10 and 12 (stiffener flanges) and IL8, 9 and 23 (upper plate), under the four traffics and for the two fatigue classes. A comparison for the IL J8 with the results of the calculation done in 1995 with the traffic measured on the bridge of Tancarville, shows consistent conclusion: the lifetimes were resp. 136 and 565 years in fatigue class 50 and 71, instead of 62 and 586 with the current traffic of the Normandy bridge (A29).

Table 4 – Lifetimes (in years) calculated for each traffic and influence line.

	Class 50				Class 71			
Traffic	A29	A20	RN4	A9	A29	A20	RN4	A9
IL J7	32	29	24	7	254	296	274	75
IL J10	11	7	6	2	57	40	33	10
IL J12	691	237	131	43	61279	35145	13445	4426
IL J8	62	46	45	10	586	588	573	113
IL J9	22173	-	8644	1469	∞	∞	∞	∞
IL J23	1141	-	614	102	208381	-	755054	95738

For the current traffic (A29), in class 71 the details are well designed and the lifetimes acceptable, except may be for the IL J10 which gives a bit too short lifetime. The results are quite close for the 2 other traffics of A20 and RN4. However, the bridge of Normandy is not designed to support a very heavy and dense traffic such as of the A9 motorway.

4.3 Lifetime Reduction with the Abnormal Loads

We now only consider the details with the shortest lifetimes, i.e. IL J7, 8 and 10. For the three other details, the safety margin is high enough to ignore the abnormal loads. The first step is to assess the individual impact of each abnormal vehicle, G1, G2, C1 and C2. Using the stress cycles of the Table 3, the Miner's law and the S-N curves (for each fatigue class) the maximum number of crossings are calculated (first lines in each cell of Table 5).

Then dividing these numbers by 600 (number of crossings assumed per year), the lifetime under each abnormal vehicle alone are calculated (2nd line of each cell in Table 5). The relative lifetime reduction r due to one abnormal vehicle, crossing the bridge 600 per year is calculated as follow:

$$\frac{1}{T} = \frac{1}{T_1} + \frac{1}{T_2} \tag{1}$$

$$r = \frac{T_1 - T}{T_1} = \frac{T_1}{T_1 + T_2} \tag{2}$$

where T_1 and T_2 are the lifetimes under the A29 traffic loads (Table 4) and under the abnormal vehicle alone (Table 5, 2nd line of each cell), T is the resulting lifetime. The values of r (in %) are given in Table 5 (3rd line of each cell). The lifetimes T_1 and T_2 are both slightly under-estimated, because the traffic increased quickly since the bridge opening and no abnormal loads crossed the bridge since that time. Therefore, the ratio r should be quite realistic.

Table 5 – Effect in fatigue of the abnormal vehicles (one by one).

Influence line	Crane G1		Crane G2		Vehicle C1		Vehicle C2	
	Class 50	Class 71	Class 50	Class 71	Class 50	Class 71	Class 50	Class 71
IL J7	1.693 2 823 1.12%	9.778 16 296 1.53%	1.650 2 751 1.15%	9.530 15 883 1.57%	2.495 4 158 0.76%	13.754 22 923 1.10%	1.253 2 088 1.51%	4.124 6 873 3.56%
IL J10	0.963 1 606 0.68%	4.349 7 248 0.78%	0.924 1 540 0.71%	4.348 7 247 0.78%	1.394 2 323 0.47%	5.354 8 923 0.63%	0.697 1 161 0.94%	2.140 3 567 1.57%
IL J8	2.293 3 821 1.60%	13.238 22 063 2.59%	2.276 3 793 1.61%	13.140 21 900 2.61%	3.460 5 766 1.06%	19.976 33 293 1.73%	1.561 2 689 2.25%	6.280 10 467 5.30%

In each cell: first line = number of crossings allowed (in millions), second line = lifetime under the single abnormal vehicle (600 runs per year), third line = percentage of the lifetime under the A29 traffic.

The contributions of each abnormal vehicle G1, G2 and C1 to the total damage in fatigue and thus to the lifetime reduction remain below 2.6%, but for the vehicle C2 for which this rate reaches 5.3% (for the longest lifetime). These values are very limited with respect to the uncertainties of the Miner's law and fatigue calculation. Moreover, the effects of the abnormal vehicles C1 and C2 are overestimated, because they have wide twin tires on the tandem axles (2 x 0.37 m instead of 2 x 0,24 m for common dual tires), and above all 8 wheels on the 5-axle group. Thus, a much more transversally spread of the loads significantly reduces the stress intensity in the stiffeners and upper plate. The influence lines used where measured for standard twin tire axle. The influence lines adapted to such wide tires or multiple wheel axle would be flatter, and thus would reduce the calculate fatigue damage. Table 6 recapitulates the global lifetime reduction under the 4 abnormal loads cumulated to the A29 traffic.

Table 6 – Global effects and lifetime reductions under the four abnormal vehicles.

	Class 50				Class 71			
	A29	4 abn. veh.	Final	r	A29	4 abn. veh.	Final	r
IL J7	32	696	31	4.40%	254	3190	235	7.37%
IL J10	11	390	10.7	2.74%	57	1496	55	3.67%
IL J8	62	934	58	6.22%	586	4618	520	11.3%

5. Conclusions

The study carried out for the concessionaire of the Normandy bridge, over the Seine river, allowed to assess the real traffic loads on the bridge, in the south-north direction. These traffic data, recorded by a bridge WIM system over more than 7 months, combined with the influence lines measured in 1995 provided an estimation of the lifetime of the most sensitive details in fatigue, the welds between the longitudinal stiffeners and the upper deck plate. These lifetimes were in good agreement with the initial estimation made in 1995 with the traffic of the Tancarville bridge. The lifetimes obtained with some similar traffic data recorded on other highways and motorways are consistent.

An estimate of the fatigue damage induced by four abnormal vehicles, two cranes of 96 and 108 t, and 2 standard vehicles of 94 and 120 t, was calculated with some conservative assumptions on their potential frequencies. It was shown that these abnormal loads would not reduce the lifetimes by more than 5 to 10%, which provide some guarantee that allowing abnormal loads up to 120 t on the Normandy bridge is feasible without too much risk of cracking in fatigue. It would be interesting to calculate the influence lines adapted to very wide tires and multiple wheel axles, to assess more accurately the stress cycles induced by these abnormal vehicles. That would surely reduce the impact of these loads. The transverse scattering of the wheel (path) location would also reduce the fatigue damage if properly measured and taken into account.

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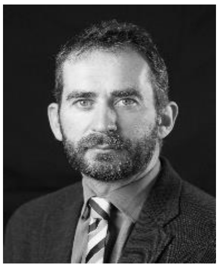
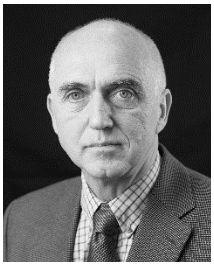
APPLICATION OF WIM DATA FOR PROBABILISTIC BRIDGE ASSESSMENT



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Abstract

This paper details a case study carried out with the aim to develop a system in which rail infrastructure may “self-assess” in order to continuously recalculate probability of failure. This was achieved through use of load models consisting of site-specific, real-time Weigh-In-Motion (WIM) data in combination with probabilistic techniques. The case study concerns an ageing steel plate girder rail bridge spanning the Ebbw River in South Wales. WIM data for trains passing over this bridge were collected from a monitoring station located less than 6km from the site. Software was created that autonomously reads this data as it becomes available and calculates the load effects induced as trains pass over the bridge. These effects were considered probabilistically and compared to those calculated using a code load model. It was thus concluded that the WIM data provides a more realistic assessment of the structural reliability.

Keywords: Weigh-In-Motion, Probabilistic Assessment, Structural Health Monitoring, Train Loading, Railway Bridge, Structural Safety

Résumé

Ce document décrit une étude de cas réalisée de développer un système dans lequel l'infrastructure ferroviaire peut «s'auto-évaluer» afin de recalculer en permanence la probabilité de défaillance. Cela a été atteint grâce à l'utilisation de modèles de données WIM (Weigh-In-Motion) en temps réel et spécifiques à un site, combinées à des techniques probabilistes. L’étude de cas concerne un vieux pont-rail en acier sur la rivière Ebbw, dans le sud du Pays de Galles. Les données WIM des trains traversant ce pont ont été collectées d'une station de surveillance située à moins de 6 km du site. Logiciel a été créé pour lire ces données au fur et à mesure de leur disponibilité, et calculer les pont effets induits par le passage des trains. Ces effets ont été considérés probabilistiquement et comparés à ceux calculés par un modèle de code. Il a donc été conclu que les données WIM fournissaient une évaluation plus réaliste de la fiabilité structurelle.

Mots-clés: Pesage en Marche, Évaluation Probabilistes, Surveillance Structurale de Santé, Chargement du Train, Pont Ferroviaire, Sécurité Structurale

1. Introduction

One of the main issues faced by bridge managers today is the maintenance and replacement of ageing infrastructure. This is often costly, labour intensive and sometimes unnecessary. Deterministic assessment using design and assessment standards is a common approach in the analysis of existing infrastructure. However, the load models described in these standards are developed to account for a wide variety of vehicle parameters passing over a range of infrastructure types. Hence in many cases they are conservative, leading to overly-regular maintenance and disruption to services. Conversely, excessively infrequent maintenance can lead to failure of infrastructure and reduced safety for users. Both cases can result in higher costs to network managers (O'Connor et al., 2009). It is therefore desirable to obtain a more accurate interpretation of the integrity of infrastructure.

The objective of this case study was to combine probabilistic techniques and site-specific, real-time Weigh-In-Motion (WIM) data to transform a rail bridge into an intelligent, self-learning object. A software platform has been developed which will allow semi-real time streaming of WIM data to the probabilistic assessment software as it is being measured. The software makes use of statistical updating to recalculate the failure probabilities of the structure continuously as new data becomes available. Future work will consider probabilistic extrapolation to allow for the estimation of future failure probabilities. The ongoing reliability can then be re-calculated over time at a chosen limit state. In this way, the bridge will become artificially intelligent, continuously "self-assessing".

The methodology first required a deterministic assessment of a rail bridge to determine its most critical elements at ULS. These elements were then assessed probabilistically using both a code load model and train WIM data. This analysis returned values for reliability (β) and probability of failure (P_f) for both load cases. The bridge in question is a steel girder railway bridge managed by Network Rail, which spans 24m across the River Ebbw in South Wales (see Figure 1). It is located between Newport and Cardiff, two of the most populated cities in Wales. It was constructed in 1966 and consists of two symmetrical independent single-span bridges, each carrying a single track. The superstructure of each span consists of two welded steel plate girders with a cross section as detailed in Figure 1. Cross-girders at 2' centres (approximately 610mm) span between the main girders to support the bridge deck. These cross girders are of T or I-section and are welded to a 15mm steel plate along their length.

Figure 1 – View of the Ebbw Bridge at track-level and the main girder cross section

The relevant tracks are considered a "main" line with a speed limit of 75 mph (approximately 120 km/h) as opposed to an adjacent bridge which is intended for slower-moving trains. Network Rail provided data consisting of information for each train that passes over the bridge. The monitoring hardware is located 5.7km from the bridge and is intended as a wheel-defect warning system. However, the hardware also records axle loads and spacing in a manner similar to pavement-based Weigh-In-Motion (WIM), which may be used to model real structure loading.

2. Deterministic Assessment

2.1 Finite Element Model

In order to determine the force and moment data for each of the bridge elements, a Finite Element (FE) model was created. The model was built in the Midas Civil software package. An image of the model highlighting the individual bridge member types may be seen in Figure 2. The model was developed based on pre-construction drawings supplied by Network Rail and does not take possible degradation of materials or member section loss into account. The effects of such defects were assumed to be negligible based on a recent bridge inspection report. Only one of the two independent spans were modelled due to symmetry. The chosen span carries the main line track with trains travelling inbound towards Cardiff.

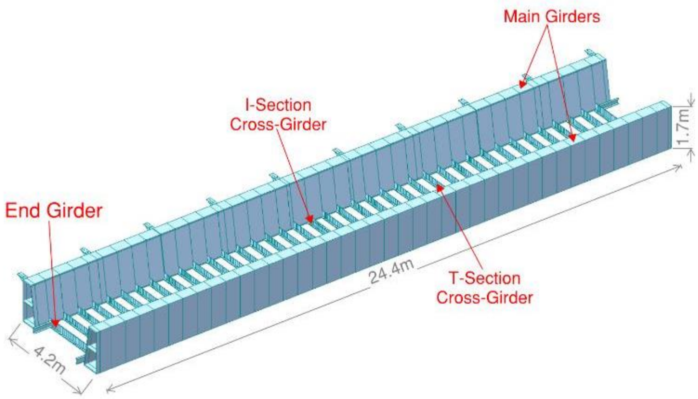


Figure 2 – FE model of the bridge (deck plate omitted for clarity)

The FE model was developed using linear elastic beam elements for all members except the deck plate which was modelled using plate elements. These plate elements were fixed rigidly to the cross girders to represent composite action due to the welding of the girders to the plate. The weight of the ballast, rails and sleepers were defined in the model based on their weight per unit bed length as per EN 1991-1-1 (2002). These values were 8.1kN/m^2 for the ballast and 1.2 kN/m^2 for the rails and sleepers. Both loads were applied over the entire bridge deck. The moving load model applied to the FE model was Load Model 71 (LM71) as defined for railway bridges in EN 1991-2 (2003).

2.2 Deterministic Analysis

A deterministic analysis was carried out for each of the individual bridge cross sections and the most highly stressed connections in order to identify the most critical elements. The partial factors applied for the critical load combination are illustrated in Table 1. These are in accordance with BD 21/01 (2001) and BS 5400-3 (2000).

Table 1 – ULS Partial Load Factors

Load Type	γ_{fl1}	γ_{fl3}
Live	1.5	1.1
Dead	1.05	1.1
Superimposed Dead	1.2	1.1

BD 37/01 specifies the use of the RU load model for the assessment of railway bridges for all combinations of rail vehicles in Europe and the UK. This load model consists of four 250kN axle loads at 1.6m spacing preceded and succeeded by an 80 kN/m UDL spaced 0.8m from the outside axle loads and continuing without limitation (see Figure 3). This load model is identical to the LM71 moving load applied in the FE model.

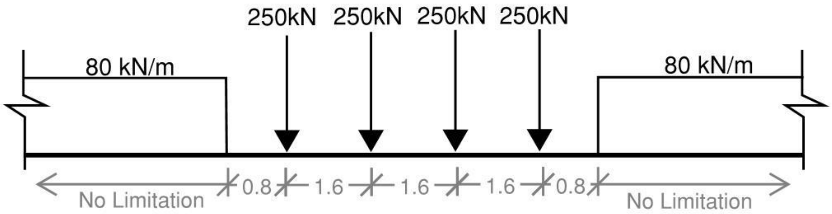


Figure 3 – Load Model 71

A steel grade of BS15 is specified in the bridge drawings, with a yield stress of 247 MPa for thicknesses less than 20mm and 230 MPa for all thicker elements (BD 21/01, 2001). The flanges of the built-up girders were detailed with Notch Ductile Steel 2B which has a yield strength of 235 MPa.

Dynamics were accounted for in the deterministic assessment through use of a Dynamic Amplification Factor (DAF) as described in BS 5400-2 (2006). These values were calculated individually for bending and shear. The DAF for bending was found to be 1.705 and 1.198 for the cross girder and main girder elements respectively. For shear, the values were 1.470 and 1.132 for the cross girders and main girders respectively.

The results of the deterministic analysis are summarised in Table 2. This table identifies the most critical check for each assessed element and the associated utilisation values. It is clear from these results that the most critical bridge member is the main girder, with a utilisation value of 101.98% in yielding. This is followed by the T-section cross girder which has a utilisation of 94.16% in yielding and the most stressed connection between a cross girder and the main girder has a utilisation of 65.80% in combined tension and shear. Hence these were the elements chosen for use in the probabilistic analysis.

Table 2 – Results of deterministic assessment

Member	Tension/Compression	Critical Check	Utilisation
Main Girder	Compression	Yielding	101.98%
T-Section Cross Girder	Tension	Yielding	94.16%
I-Section Cross Girder	Tension	Yielding	69.50%
Cross Girder Connection	Tension	Tension/Shear	65.80%

3. Weigh-in-Motion Data

The WIM data referred to in this paper is data collected from a Wheel Defect Detection (WDD) system at Marshfield, a site 5.7km from the Ebbw bridge. The WDD system in consists of an arrangement of 6 fibre optic sensors on each rail, each an independent measurement unit with its own calibration. As a vehicle passes over the monitoring site, each sensor measures both static and dynamic forces induced by that vehicle. The system will then combine the individual forces to compute output values for static forces, axle weights and imbalances. Dynamic impact forces are also calculated, from which wheel defect data may be obtained. The system operates with a wheel recognition feature which takes values for axle count, spacing and speed and can identify the vehicle type passing over it (Venekamp, 2017). Vehicle tags are also picked up by the system, allowing sensors to be automatically calibrated when a vehicle of known weight passes the site. The sensors in use at Marshfield are calibrated several times per day, resulting in a maximum error of ±3% at the vehicle level, meaning that the actual weights could be 3% above or below the recorded value. This measurement error is a function of the state of motion of the vehicle as well as the quality of the track at the monitoring location (Venekamp, 2017).

For the purpose of this case study, Network Rail initially provided 46 days of data from the Marshfield site. There are no junctions between the two locations, thus all traffic passing over the bridge must also pass through the monitoring site. Figure 4 shows a histogram of all individual axle weights recorded in this 46 day period. As previously stated, the RU model consists of axle weights of 250kN. This value is illustrated in the figure with a broken vertical line. It is worth noting that there are a total of 482 axles recorded in the 46-day period with values exceeding 250kN. The heaviest recorded axle had a weight of 288kN.

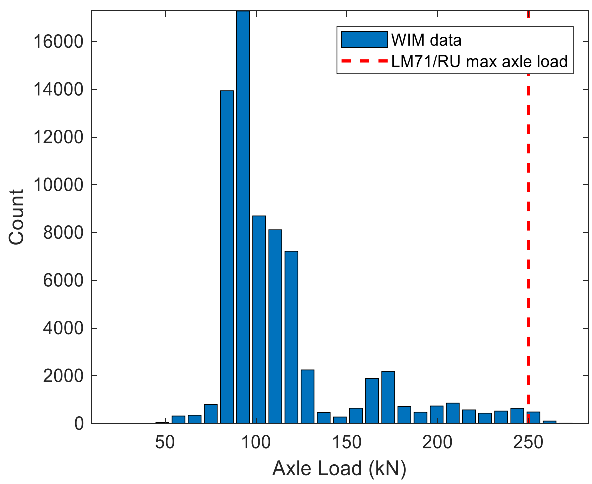


Figure 4 – Axle load histogram for all trains at the Ebbw Bridge

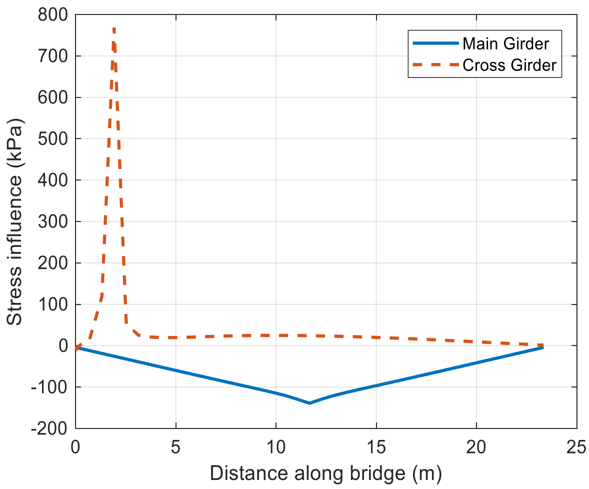


Figure 5 – Stress influence lines for the main girder and T-girder

4. Probabilistic Assessment

This case study involves the performance of two probabilistic assessments at ULS for each of the chosen critical elements; one using a code load model and the other using site-specific WIM data. Both analyses were carried out by applying these moving loads across the influence lines for the critical bridge elements. The influence lines were extracted from the FE model for the left and right rails independently and were combined within the assessment software. The influence line analysis and probabilistic modelling was coded in MATLAB.

Stress was deemed to be the most critical factor in the deterministic analysis of the T-girder and the main girder and so their stress influence lines were extracted (Figure 5). It is clear from this figure that the main girder is influenced by global effects (i.e. the train load arrangement), while local effects (i.e. individual axles) are more critical for the T-girder element. Combined tension and shear governed the failure of the connection and so these influence lines were combined for the connection analysis.

4.1 Permanent Load and Resistance Modelling

Probabilistic assessment of structures involves the stochastic modelling of certain load and resistance variables. This modelling allows for reasonable physical variation in these parameters to be taken into account in calculations. In this study, each of the relevant parameters was modelled based on distributions outlined in DRD (2004).

4.1.1. Dead Load and Superimposed Dead Load

In both the DL and SDL cases, the loads were modelled as normal distributions with mean values equal to the values obtained from the deterministic assessment (see Table 3). The DL was then modelled with a coefficient of variation (CoV) of 5%, while the SDL was modelled with a CoV of 10% as per DRD (2004). Uncertainty in both models is considered to be a normally distributed variable with a mean of 0.0 and a standard deviation of 5% and was applied to each model individually by multiplication with the base distributions.

Table 3 – Mean Values for Stochastic Load Models

Element	μ_{DL}	μ_{SDL}
T-Section Cross Girder (MPa)	5.6	9.6
Main Girder (MPa)	17.3	18
Connection Tension (kN)	0.2	0.4
Connection Shear (kN)	0.2	0.4

4.1.2. Resistance

The resistance capability of the structural elements was modelled based on the yield strength of the material. This variable was modelled stochastically using a lognormal distribution and mean (μ) values of 304MPa and 283MPa for the T-girder/connection and main girder, respectively, and a standard deviation (σ) of 25MPa for all elements (DRD, 2004). Uncertainty in the resistance model was modelled with a lognormal distribution and a CoV based on a variable I_f with criteria as defined in DRD (2004). Considering the uncertainty in this way allows potential inaccuracies in the load and FE model to be considered. The combination of these criteria resulted in a CoV value for uncertainty in the material strength of 0.087.

4.2 RU Load Model

4.2.1. Load and Uncertainty Modelling

Connolly et al. (2016) determined that RU loading may be modelled stochastically assuming a Gumbel distribution with a 98% fractile equal to the RU load model as defined in BD 37/01 (2001). For the purposes of this study, a conservative CoV of 0.2, resulting in a mean wagon weight of 0.66 times the RU load model (Connolly et al., 2016). Uncertainty in the RU load model was modelled stochastically as a normally distributed variable with a mean of 1.0. The variation in the uncertainty model was generated based on the level of confidence in the accuracy of the applied load. In this load case, the uncertainty was considered to be “medium”.

This implies an assumed accuracy of ±25% as per DRD (2004). Hence a CoV for the uncertainty model was calculated as 0.15.

4.2.2. Dynamic Amplification

As defined in DRD (2004), the DAF was modelled as in Equation (1) below.

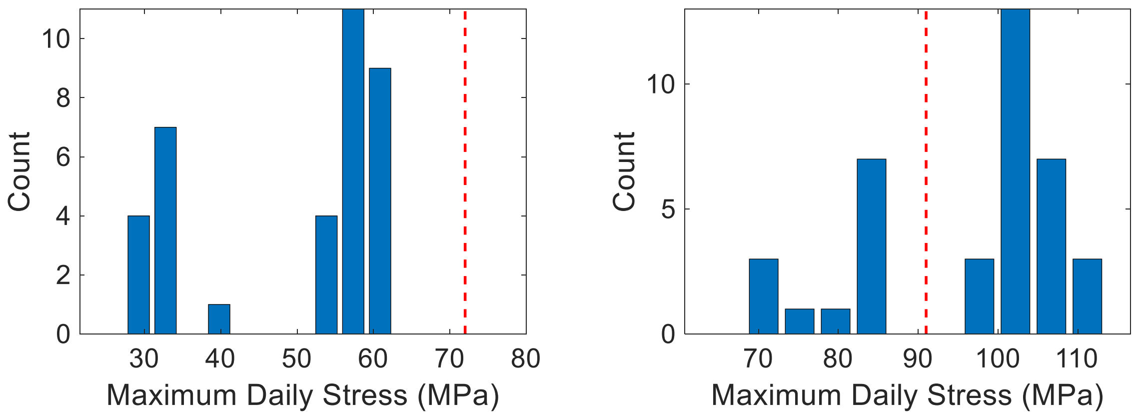
$$K = 1 + \varepsilon \qquad (1)$$

Where K is the modelled DAF and ε is the dynamic increment. This dynamic increment was modelled stochastically as a normally distributed variable with a CoV of 1.0 and a mean value which resulted in a 98% fractile value equal to that of the deterministic dynamic factor. These mean values were 0.231 for the T-girder and 0.039 for the main girder.

4.3 WIM Data Model

4.3.1. Load Modelling

The WIM data used in this study consisted of 46 days of train loading data. When considering assessment at ULS, it is primarily the maximum load effect values that are of interest. Figure 6 shows the maximum daily load effects obtained for the a) main girder and b) T-girder by running the WIM data over their stress influence lines. In both figures, the equivalent maximum stress induced by the RU load model is illustrated with a broken vertical line. For the main girder, it can be seen that the RU load model is conservative in comparison to the WIM stress values. However, for the T-girder, there are a significant number of instances where the WIM data induces greater load effects than the RU load model. This is due to the more localised nature of the T-girder influence line and the presence of axle weights exceeding 250kN.



(a) (b)

Figure 6 – Max. daily stresses in a) the main girder and b) the T-girder

In order to effectively perform the probabilistic assessment, it was necessary to calculate the maximum yearly distribution of the live load effects due to the train. In order to do this, all of the WIM data was plotted on probability paper and a GEV distribution was fitted to the tail of the data, i.e. the final 1% of values. This distribution could then be extrapolated into maximum yearly values using Extreme Value Theory (EVT), outlined in Equation (2).

$$F_Y(y) = [F_X(x)]^n \qquad (2)$$

Where the parent distribution F_x is raised to a power n in order to produce a maximum distribution F_y. This maximum distribution will consist of n independently distributed samples of x (Connolly et al., 2017). As only working days were to be considered in this assessment, the n-value was taken to be 303, i.e. one year excluding Sundays and public holidays.

4.3.2. Uncertainty Modelling

As in the RU load case, uncertainty was modelled as a normally distributed variable with a mean of 1.0. However, the use of WIM data leads to a higher level of confidence in the accuracy of the applied load model and so the CoV was lowered to 0.1 (DRD, 2004). This CoV is in line with a confidence of ±15% and so could be considered to be conservative when compared to the stated accuracy of ±3% of the WDD sensors.

4.3.3. Dynamic Amplification

The DAF applied to the WIM data load model was calculated as per the procedure for real trains outlined in EN 1991-2 (2003) and illustrated in Equation (3) below. Where φ' is the proportion of the DAF applicable for a track in perfect condition and φ'' is the proportion representing track irregularities.

$$DAF = 1 + \varphi' + \varphi'' \tag{3}$$

As in the RU load case, the DAF is considered to be a stochastic variable. However, it is specified that φ' is correct for 95% of cases while φ'' is a constant value. Therefore, only the φ' will be modelled probabilistically and φ'' will be added deterministically to the model.

The distribution to be applied to φ' was determined by consulting the dynamic loads for each axle as recorded in the WIM data. It is noted that these DAFs are a function of wheel irregularities rather than vehicle-bridge interaction and so cannot be applied directly to the load model. However, the variation of these values is a good estimate of the variation that would exist in the bridge DAFs as they are caused by the same train variations. KS testing showed that a lognormal distribution is a good fit to these dynamic increments and as Connolly et al. (2016) has shown, a lognormal distribution provides a good model for dynamic increments in real train situations. Hence φ' was modelled using a lognormal distribution with a CoV of 0.562, matching the distribution fit to the WIM data. The mean of the distribution was then calculated using least-squares optimisation between then 95$^{\text{th}}$ percentile of the CDF and the deterministic value. These means calculated were 0.273 for the T-girder and the connection and 0.049 for the main girder.

4.4 Reliability

Reliability is a measure of structural safety at a given limit state. It is quantified by the reliability index (β) and is a function of the probability of failure (P_f) for an element or system. In this case study, the reliability of the bridge was calculated using the First Order Reliability Method (FORM) (Choi et al., 2007) which is based on a performance function *g(X)*. The FORM analysis was programmed in MATLAB. When considering ULS analysis, the performance function may be described by Equation (4).

$$g(X) = R(X) - S(X) \tag{4}$$

Where R and S are the resistance and loading of the system, respectively. Hence when $g(X) < 0$, the load exceeds the resistance and ULS failure has occurred. The Rackwitz-Feissler method was used to transform the stochastic variables into standard normal space. The Hasofer-Lind method of FORM analysis was then used to calculate the reliability index as outlined in Choi et al. (2007).

The minimum reliability standard to be achieved by structures is defined by the target reliability index. There are a number of standards that specify target reliability indices for a range of different scenarios, however the values outlined under JCSS (2000) are considered to be the most appropriate in this case. For the Ebbw bridge, the costs of safety measures and consequences of failure are both considered to be "normal", therefore a target (minimum) reliability index of 4.2 is specified.

5. Results of Analysis

As shown previously, a deterministic assessment of the individual elements of the bridge returned high utilisation values for the critical main girder and T-girder elements. Relatively high utilisation was also calculated for the most critical cross-girder connection, indicating members that are close to, or exceeding, capacity. Each of these elements was assessed probabilistically using both an RU load model and a WIM data model. The results of these analyses may be seen in Table 4.

Table 4 – Probabilistic and deterministic results for the critical elements

	β		Utilisation
Element	RU Model	WIM Model	Deterministic
T-Section Cross Girder	3.77	2.62	94.16%
Main Girder	4.96	6.70	101.98%
Cross Girder Connection	6.13	5.95	65.80%

These results show that in the case of the main girder, the reliability index calculated using the WIM data exceeds the value obtained using the RU load model. This is to be expected given the conservative nature of the RU model when used on a global influence line. It is also worth noting that while the main girder achieved a utilisation value exceeding member capacity in the deterministic assessment, the reliability indices calculated probabilistically are both higher than the target value (4.2), indicating that the element has sufficient capacity. Conversely, in the case of the T-girder and cross girder connection, the β-values calculated using the WIM data model are less than those obtained using the RU load model. Additionally, both probabilistic results in the case of the T-girder are significantly less than the target reliability index, indicating insufficient safety where the deterministic assessment indicated no limit state failure. This is likely due to the significant influence of localised effects on the T-girder in combination with the presence of axle loads exceeding the RU maximum of 250kN.

6. Conclusions

The results of this case study showed that the developed software was capable of using site-specific WIM data to perform an accurate analysis of critical bridge elements using probabilistic methods. In the case of the main girder, the WIM data model returned higher reliability indices than the RU model and indicated a greater level of safety than was shown in the code load model and the deterministic assessment. In two of the other critical elements, the T-girder and cross girder connection, the WIM model returned a lower level of safety than was calculated using the more traditional methods. Analysis of the WIM data found that there were a significant number of axles weighing more than the RU-defined maximum of 250kN. These axles would not have been considered in either the deterministic or RU-loaded probabilistic analyses, indicating a lack of dependability in these traditional models in this case. It should be noted that the analysis performed here did not consider structural robustness / redundancy, which may provide higher reliability levels than those calculated in this paper.

Thus it may be concluded that the use of a model with WIM data specific to the bridge in question creates a more flexible model that can more accurately mould itself to represent the real behaviour of the structure. This can then provide network operators with a more reliable measure of the probability of failure of the structure, optimising bridge maintenance.

7. Acknowledgments

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EFFECT OF QUALITY OF WEIGH-IN-MOTION DATA ON LOAD EFFECTS ON BRIDGES



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Abstract

Although quality of weigh-in-motion (WIM) data influences the results of bridge (and pavement) load modelling, no clear recommendations existed about how accurate the results of WIM measurements should be to provide reliable prediction of load effects on bridges. Only the COST 323 specifications suggested that the accuracy class of the WIM results should not be less than C(15). Parametric studies using two different sets of WIM data were performed to estimate the effects of bridge-WIM setup, of temperature effects on measurements, and of automatic and manual data control on calculated load effects on bridges. The results show that data quality verification must be applied. The proposed auto-cleaning and automated quality checking procedures proved effective as the resulting load effects were within a few percent of the final values, calculated from the highest quality datasets, in which all vehicles were visually verified. Results also suggested that visual verification of all results, as often used in the past, is not needed, and that the vehicles with minor errors and inconsistencies will result in negligible changes with respect to calculated load effects.

Keywords: accuracy, B-WIM, data quality, measurement error, weigh-in-motion

Résume

Bien que la qualité des données de pesage-en-marche (WIM) influe sur les résultats de la modélisation de la charge des ponts (et de la chaussée), aucune recommandation claire n'existait quant à la précision des résultats des mesures WIM pour permettre une prévision fiable des effets de la charge sur les ponts. Seules les spécifications COST 323 donnent à penser que la classe d'exactitude des résultats WIM ne devrait pas être inférieure à C (15). Des études paramétriques utilisant deux ensembles différents de données WIM ont été réalisées pour estimer les effets de la configuration WIM, des effets de la température sur les mesures et du contrôle automatique et manuel des données sur les effets de charge calculés sur les ponts. Les résultats montrent que la vérification de la qualité des données doit être appliquée. Les procédures proposées de nettoyage automatique et de contrôle de qualité automatique se sont révélées efficaces, car les effets de charge résultants se situaient à quelques pour cent des valeurs finales, calculées à partir des jeux de données de qualité supérieure, dans lesquels tous les véhicules étaient vérifiés visuellement. Les résultats ont également suggéré que la vérification visuelle de tous les résultats, comme souvent utilisée dans le passé, n'est pas nécessaire, et que les véhicules avec des erreurs mineures et des incohérences entraîneront des changements négligeables en ce qui concerne les effets de charge calculés.

Mots-clés: précision, B-WIM, la qualité des données, erreur de mesure, pesage-en-marche

1. Introduction

Data quality and quantity influence the results of bridge load modelling. However, until recently (Žnidarič, 2017), no clear recommendations existed about sufficient quality of WIM data, how data quality affects the results and how much data is needed for reliable prediction of load effects. The only criteria, based on engineering judgment, were given in the European specifications for WIM (COST 323, 2002), where it is suggested that:

- accuracy of WIM data for bridge traffic load modelling shall be of at least class C(15), or roughly 95 % of gross weights within ±15 % and axle loads within 20 % of the static values, and that
- as many vehicle records as possible (but at least 100 000) shall be used.

This paper describes results of a study that focused on various aspects of WIM data quality and their effect on the results of bridge traffic load modelling.

2. Using WIM data to calculate load effects on bridges

2.1 Bridge WIM

All data in the study was collected at two different sites using a bridge weigh-in-motion (B-WIM) system. B-WIM refers to a method that uses an instrumented bridge or culvert to weigh the heavy vehicles that cross the structure. These systems provide equivalent set of vehicle parameters (axle loads, gross weight, axle spacing, velocity, vehicle category…) as the pavement WIM systems. A typical installation of an underpass under a four-lane highway is shown in Figure 1. The central sensors are used for weighing and the additional pairs of sensors, one pair per lane, are used to determine vehicle velocities and, from there, axle spacings.

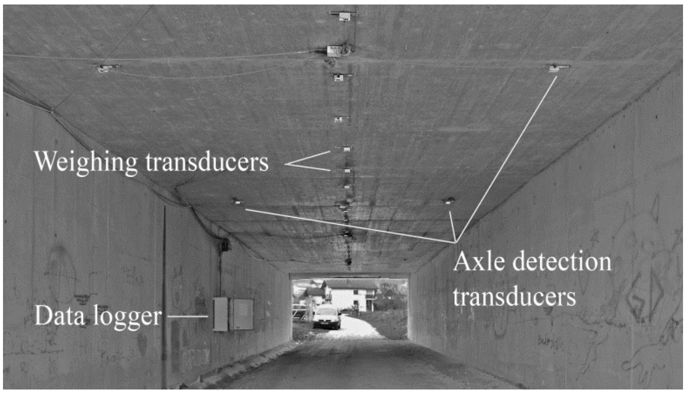

Figure 1: Typical installation of an underpass with a B-WIM system

B-WIM systems have some specific advantages (Žnidarič et al., 2017):

- The hardware is completely portable and can be moved from one bridge to the other.
- Accuracy of results on smooth pavements is high. Installations on rougher surfaces, where pavement WIM would not even be considered, can provide reasonably accurate results.
- Installation and maintenance activities do not interrupt the traffic as all sensors are mounted underneath the bridge deck. This is advantageous on sites where cutting into the pavement is not allowed, when installation of a pavement based system is not feasible due to heavy traffic or if permits for road closures are difficult to obtain.
- Collected strains records can be used to generate bridge related indicators (influence lines, dynamic amplification factors, girder factors), which optimise the analytical models used in structural assessment (ARCHES D16, 2009; Žnidarič et al., 2012).

The obvious weakness of B-WIM method is that a suitable bridge is not always available. Furthermore, while instrumenting common slab or beam-and-slab bridges is straightforward, setting-up a less common structure requires substantial knowledge about bridges.

2.2 Convolution method

Convolution method was used to model the expected maximum load effects on bridges. This is an established statistical technique that is computationally less demanding than the full simulations (Richardson et al., 2014). Moses & Verma (1987), ARCHES project (2009) and Žnidarič (2017) have shown that it gives similar results to Monte Carlo simulation, if the assumption of independent traffic in the two adjacent lanes is valid.

The convolution method assumes that the highest load effect is achieved when two vehicles from independent traffic flows are placed side by side on a bridge at the location of maximum load effect, which is defined as a loading event. In Europe, such approach can be justified on over 90 % of bridges (SAMARIS D19, 2006; Žnidarič et al., 2011) on which influence lines are shorter than 30 m. On these bridges the critical event happens due to *one* vehicle in each of the two traffic lanes. The combined distribution from both traffic lanes is extrapolated to the number of expected critical events, in this case meeting of two heavy vehicles on the bridge. In this study extrapolation to the 75-year values of load effects was applied.

Traffic load modelling procedures, probability distribution of extremes and other details about using convolution method to calculate load effects on bridges by far exceed the scope of this paper and are given for example in (Žnidarič, 2017) and in (Žnidarič et al., 2018).

It should be noted that this analysis does not deal with the extremely heavy transports, which load effects can in some rare cases exceed those from the forecasted normal traffic. Such situations must be considered individually.

3. Quality of WIM data

Quality of weigh-in-motion (WIM) data influences the results of bridge (and pavement) load modelling. The main goal of the study presented here was to investigate whether application of the following procedures affects the calculated bridge load effects:

(a) What is the effect of the measuring system setup?
(b) How do long-term (environmental) effects, such as temperature variation, affect the results?
(c) How efficient is the automatic data quality control procedure?
(d) How does the detailed verification of WIM results affect the calculated load effects?

3.1 Setup of the measuring system

European Commission financed research projects TRIMM (Ralbovsky et al., 2014) and BridgeMon (Corbally et al., 2014) have yielded a number of improvements that lead to higher quality of B-WIM results. Influence of the following on the calculated load effects was tested:

(a) Calculation of bridge influence line (IL): a new robust method was developed that calculates the bending moment ILs from strain response caused by any vehicle that crosses the bridge. Individual ILs are averaged to obtain the measured bridge ILs that do not depend on the specific (dynamic) behaviour of selected vehicles that are used in other methods of calculating the actual ILs (OBrien et al., 2006; Žnidarič et al., 2017).
(b) Calculation of sensor scaling factors: on reinforced concrete bridges the accuracy of B-WIM results is often dissapointing. Common reasons are the strain measurements that do not provide the ‘ideal’ bridge response/strains under the vehicle loading. The reasons are faulty sensor attachments or, most often, strains that measure irregularities due to

the cracks in the concrete cover. Sensor locations, quality of their production and to some extent their malfunctioning (calibration that faded over time) can also affect the results and must be accounted for. A solution that multiplies the measured strains with correction factors has shown to improve the results for up to one accuracy class according to the COST 323 WIM specifications (Žnidarič et al., 2015).

(c) Strips method: the theoretical solution of using 2-dimensional influence surfaces to deal with multiple presences of vehicles in adjacent lanes is not realistic, as it would require an extremely high number of calibration runs. To overcome this, the strips method divides the measured strains not to individual sensors, but according to their contribution to the driving and the adjacent traffic lanes. This keeps the calculation procedure simple and, above all, does not require any additional expensive and time-consuming vehicle runs during the calibration procedure (Žnidarič et al., 2012).

(d) Improved axle detection methods: a number of numerical and experimental studies were performed to improve efficiency of free-of-axle detector (FAD) data acquisition (Dempsey et al., 1998). FAD instrumentation replaces the conventional axle detectors on the surface or in the pavement with extra strain sensors that capture strain signals that are, after complex signal processing, used to detect axles (Corbally et al., 2014).

3.2 Environmental effects

The response of virtually all bridges to traffic loads is affected by varying temperature:

- on integral (frame-type) structures, where displacements and rotations of support are constrained, it changes their behaviour, including the shape of the influence lines,
- material properties (stiffness) change; this applies to steel, concrete, and above all, the asphalt, in particular at high summer temperatures
- local strains, as measured for B-WIM purposes, change due to varying exposure to the sun.

The study compared the bridge load effects calculated from uncorrected results and from results that were adapted with a temperature dependent correction factor.

3.3 Automatic data quality control

A data quality system, consisting of four steps, has been developed (Žnidarič, 2017):

a) The axle reconstruction procedure attempts to find the missing axles. At the location of likely missing axle (i.e. within a double or triple axle) it inserts a virtual axle, reweighs the vehicle and calculates the Reduced-Chi Squared (RCS) value, the square of differences between the calculated and measured strain responses. If this RCS value is below the RCS value of the original vehicle, the new axle is retained.

b) In the next stage, the auto-cleaning procedure searches for typical errors, such as light non-existent axles, missing axles and unrealistic axle load distributions, and corrects them on the level of data, without reweighing.

c) Then, vehicles are grouped into subsets, according to the maximum measured strains. This vastly reduces the time spent for manual data quality control, as it identifies and allows omitting the vehicles, which generate negligible load effects.

d) Finally, the data quality assessment rules, which use the points system, are adopted. They test a number of parameters (axle loads, axle spacings, axle load configuration, axle load distribution…) if they are within the predefined thresholds. If these are exceeded, the vehicle gets up to 7 points. It the sum of all points is below 1 or less, the vehicle has no questionable characteristics and gets a green flag. If the sum is between 2 and 6 it has issues that are likely irrelevant with respect to bridge or pavement loading and gets an orange flag. Otherwise it receives a red flag and the results need to be verified for potential major errors or for confirmation of an extremely heavy vehicle.

Detailed description of these procedures exceeds the scope of this paper.

3.4 Manual data quality control

B-WIM system used (SiWIM®) allows to visually check uncertain results. The software compares the calculated and measured strains and allows, in the case of mismatch, allows to add missing or to remove excessive axles, after which it automatically re-runs the weighing procedure to obtain the corrected results. Vehicles were visually verified to test the impact of such detailed control on calculated load effects on bridges.

4. Results

4.1 Bridge A

Bridge A is a 6-m long integral slab bridge, located on a low-volume motorway. One half of dilated structure carries 2 lanes of traffic in one direction. A dataset with over 750 000 WIM records, collected over a period of 2 years, was used. Firstly, three sets of data were prepared:

1. Based on the initial setup, in accordance with the B-WIM knowledge prior to the TRIMM and Bridgemon projects (dataset 0_1).
2. Based on the optimal setup that included all improvements described in section 3.1 (optimal influence lines, sensor factors, strips, optimised axle detection), but without temperature calibrations (dataset 1_1).
3. Same as item 2, but with temperature calibration (dataset 1_2).

In the dataset 2_1 data was auto-cleaned and split into five subsets, depending on the maximum measured strain. These were quality checked with procedures described in section 3 to flag the individual vehicles as red, orange or green. In the next stages, data was step-by-step visually inspected, if necessary corrected and then approved or rejected. In dataset 3_1 this was done only for all red-flagged records. Then the orange-flagged sets of data were visually checked (datasets 3_2 to 3_6), followed by the heaviest green-flagged vehicles in dataset 3_7, and finally, with all vehicles in dataset 3_8. Detailed results are presented in Table 1.

Table 1 – Bridge A: summary of all input parameters used in the analysis

Data set	System setup & calibration	Temp.&Vel. compensated	Strain levels Red					Strain levels Orange					Strain levels Green				
			5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
0_1	Initial	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
1_1	Optimal	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
1_2	Optimal	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
2_1	Optimal	Yes	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
3_1	Optimal	Yes	M	M	M	M	M	A	A	A	A	A	A	A	A	A	A
3_2	Optimal	Yes	M	M	M	M	M	M	A	A	A	A	A	A	A	A	A
3_3	Optimal	Yes	M	M	M	M	M	M	M	A	A	A	A	A	A	A	A
3_4	Optimal	Yes	M	M	M	M	M	M	M	M	A	A	A	A	A	A	A
3_5	Optimal	Yes	M	M	M	M	M	M	M	M	M	A	A	A	A	A	A
3_6	Optimal	Yes	M	M	M	M	M	M	M	M	M	M	A	A	A	A	A
3_7	Optimal	Yes	M	M	M	M	M	M	M	M	M	M	M	A	A	A	A
3_8	Optimal	Yes	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

A	Automatic data quality control
M	Manual data quality control
No	No data quality actions

For all datasets the 75-year bending moments and shear forces at the bridge entrance were calculated according to (Žnidarič, 2017). Computations were repeated for datasets with 50 000, 250 000 and 750 000 vehicles. The full datasets were divided to subsets, for each of which the load effects were calculated and statistically evaluated.

Figure 1 presents the mean values of bending moments calculated from 750 000 vehicles. Table 2 displays all results (mean values, coefficients of variations k_{var}, minimum and maximum values), for three sizes and all variations of datasets, for bending moments and shear forces. Lines 'vs.3_8' give normalised results referenced to the manually verified (the most accurate) dataset 3_8.

Finally, the effect of the length of the influence line was investigated. Results were generated from the bending moments calculated with simply supported influence lines of five different lengths: 5, 15, 25, 35 and 45 m. Datasets again contained 50 000, 250 000 and 750 000 vehicles. Results normalised to the results from the 3_8 datasets are presented in Figures 2 to 4.

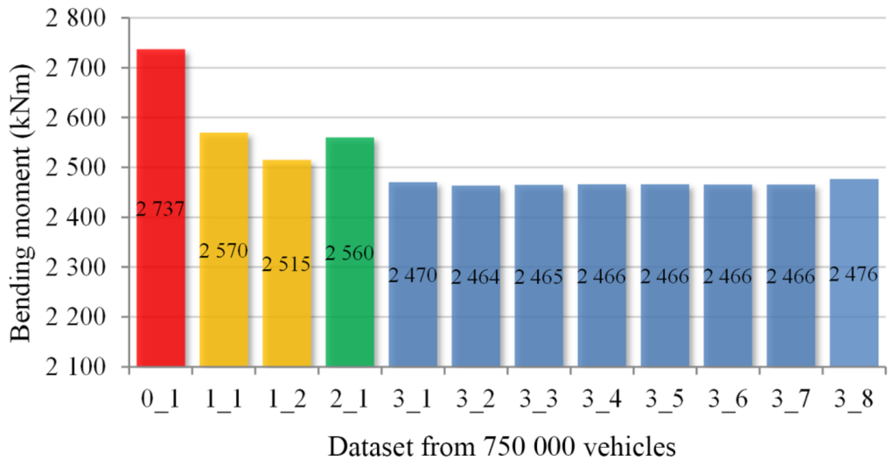

Figure 1 – Bridge A: calculated bending moments – 25 m span, 750 000-vehicle dataset

Table 2 – Bridge A: results of the WIM data quality influence on load effects

	Vehicles	Set	0_1	1_1	1_2	2_1	3_1	3_2	3_3	3_4	3_5	3_6	3_7	3_8
Bending moment	50000	Mean	2974.3	2537.7	2486.3	2497.2	2464.3	2458.4	2457.6	2458.6	2458.8	2458.5	2458.4	2466.9
		k_{var}	7.19%	6.25%	4.69%	5.55%	4.08%	4.01%	4.10%	4.10%	4.10%	4.09%	4.09%	4.27%
		Min	0.0	2238.9	2296.3	2284.6	2321.0	2320.9	2317.3	2318.3	2318.3	2317.9	2317.9	2317.7
		Max	0.0	2726.6	2706.6	2839.9	2599.4	2599.5	2600.9	2602.4	2602.5	2602.6	2602.4	2602.4
		vs.3_8	120.6%	102.9%	100.8%	101.2%	99.9%	99.7%	99.6%	99.7%	99.7%	99.7%	99.7%	100.0%
	250000	Mean	3091.1	2575.4	2512.0	2542.1	2478.4	2471.6	2472.6	2473.6	2473.8	2473.4	2473.3	2482.1
		k_{var}	2.35%	1.62%	2.38%	4.57%	0.30%	0.51%	0.47%	0.47%	0.47%	0.49%	0.49%	0.99%
		Min	0.0	2527.5	2475.2	2472.5	2472.0	2457.5	2459.6	2460.7	2460.9	2459.7	2459.7	2459.9
		Max	0.0	2605.0	2581.0	2676.3	2486.4	2481.7	2481.9	2482.8	2483.1	2483.2	2482.6	2508.7
		vs.3_8	124.5%	103.8%	101.2%	102.4%	99.8%	99.6%	99.6%	99.7%	99.7%	99.6%	99.6%	100.0%
	750000	Mean	3085.3	2570.0	2515.1	2559.9	2470.1	2463.9	2464.9	2465.9	2466.1	2465.8	2465.5	2476.5
		vs.3_8	124.6%	103.8%	101.6%	103.4%	99.7%	99.5%	99.5%	99.6%	99.6%	99.6%	99.6%	100.0%
	Average Mean		123.2%	103.5%	101.2%	102.3%	99.8%	99.6%	99.6%	99.6%	99.6%	99.6%	99.6%	100.0%
Shear forces at bridge entrance	50000	Mean	501.1	438.1	429.0	431.5	425.2	424.2	423.9	424.1	424.1	424.1	424.1	425.5
		k_{var}	6.59%	7.25%	5.33%	5.45%	5.04%	4.92%	5.03%	5.03%	5.03%	5.01%	5.01%	5.08%
		Min	0.0	384.6	396.1	401.1	394.1	394.1	393.9	393.9	394.1	394.0	393.9	393.9
		Max	0.0	486.5	465.1	479.2	458.9	456.7	456.8	457.0	457.0	456.8	456.8	459.5
		vs.3_8	117.8%	102.9%	100.8%	101.4%	99.9%	99.7%	99.6%	99.7%	99.7%	99.7%	99.7%	100.0%
	250000	Mean	517.1	448.9	434.9	437.5	429.8	428.1	428.2	428.3	428.4	428.3	428.3	429.7
		k_{var}	2.99%	1.41%	2.40%	3.50%	0.51%	0.50%	0.48%	0.48%	0.49%	0.50%	0.49%	1.05%
		Min	0.0	442.1	426.7	426.6	427.3	426.7	427.0	427.1	427.2	427.0	427.0	427.0
		Max	0.0	454.6	446.6	455.0	431.4	430.6	430.6	430.7	430.8	430.8	430.7	435.0
		vs.3_8	120.3%	104.5%	101.2%	101.8%	100.0%	99.6%	99.6%	99.7%	99.7%	99.7%	99.7%	100.0%
	750000	Mean	517.2	448.1	435.3	440.0	428.4	426.8	426.9	427.0	427.0	427.0	427.0	428.3
		vs.3_8	120.8%	104.6%	101.6%	102.7%	100.0%	99.6%	99.7%	99.7%	99.7%	99.7%	99.7%	100.0%
	Average Mean		119.6%	104.0%	101.2%	102.0%	100.0%	99.7%	99.6%	99.7%	99.7%	99.7%	99.7%	100.0%

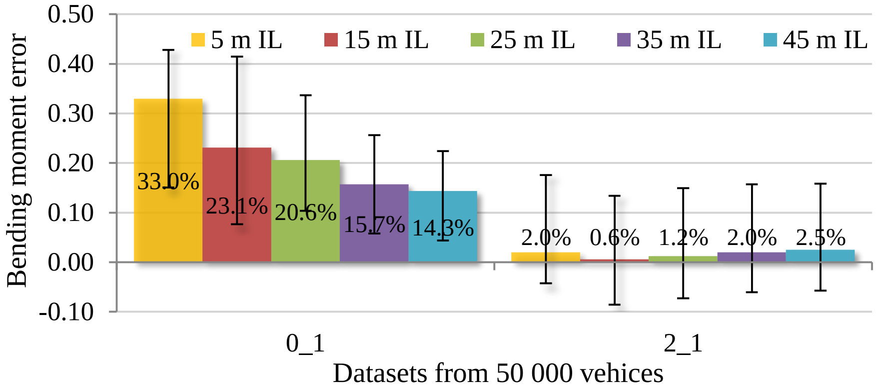

Figure 2 – Bridge A: bending moment errors for different quality datasets and different spans – mean values and min-max intervals of 50 000-vehicle datasets

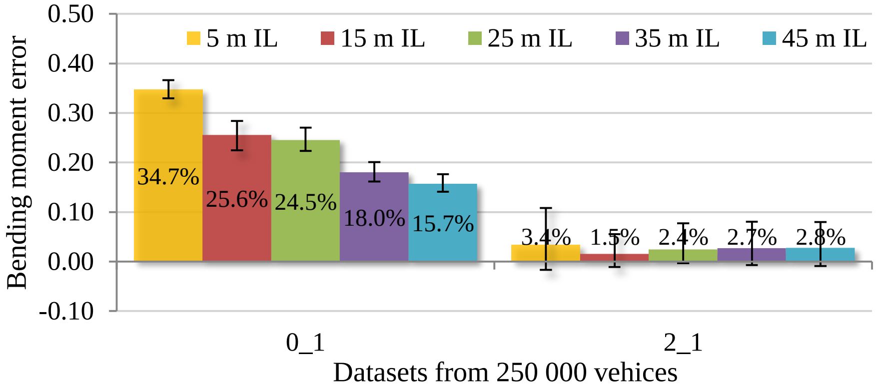

Figure 3 – Bridge A: bending moment errors for different quality datasets and different spans – mean values and min-max intervals of 250 000-vehicle datasets

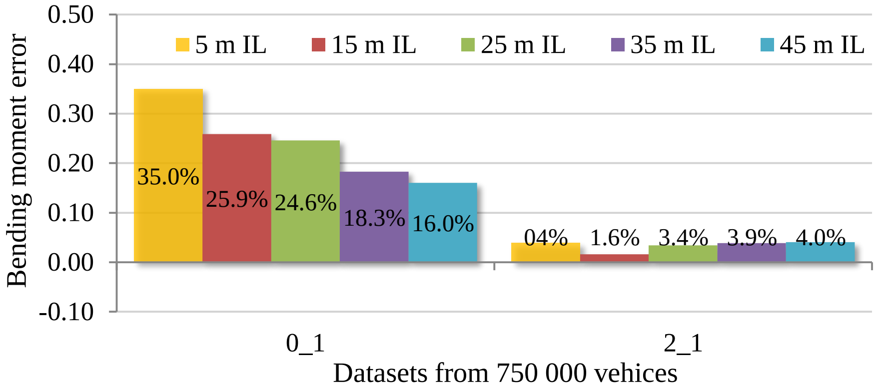

Figure 4 – Bridge A: bending moment errors for different quality datasets and different spans – mean values of 750 000-vehicle datasets

The results yield the following conclusions, valid for the bending moments and for the shear forces at bridge entrance:

1. Initial dataset 0_1 has given on average over 20 % higher values than the most accurate, visually validated dataset 3_8. Differences are greater for shorter than for longer spans.
2. Dataset 1_1, based on new developments, but without temperature calibration reduced the difference to 4.0 %.
3. Adding temperature calibration further reduced the average error to 1.2 % of their final values.

4. Adding automatic data quality control procedure (dataset 2_1) has increased the load effects for almost 2 %.
5. Visual inspection of all red-flagged vehicles rescued some heavy vehicles, but reduced the results for over 3 %, practically to the final values.
6. Gradual visual inspection of all orange-flagged and green-flagged vehicles resulted in negligible variations of up to 0.4 %.

The only substantial differences in the results were observed:

- between the old type of instrumentation and setup and the new ones, which accounted for all improvements from section 3.1; this narrowed the gap with respect to the end results to 4 %, and
- after applying the data quality check; in this case, the automatic procedure had little effect, the remaining error was removed after visual validation of all red-flagged vehicles.

4.2 Bridge B

Bridge B was similar to Bridge A, except that the span was 12 m. This dataset was used as a high-density traffic alternative to traffic from the other bridge and contained considerably less data than the previous example. In this case, only three datasets were generated:

- as measured, using the optimal possible setup of the B-WIM system (denoted as 'Measured', equivalent to 1_1 dataset from Bridge A),
- after applying the automatic quality control (denoted as 'AQC', equivalent to 2_1 dataset from Bridge A),
- after visually inspecting all records ('Final').

With these datasets, the differences between the optimal measured results, which included all improvements described in section 3.1, and those processed with the automatic quality control algorithms, were as high as 25 % for bending moments and 22 % for shear forces, compared to almost no difference between the Bridge A datasets 1_1 and 2_1. The main reason for the large difference on this site was the very lively bridge, which resulted in high number of missed axis, particularly from the axle groups. Consequently, over one third of vehicles were flagged orange, compared to below 3 % on the Bridge A. The missed axes caused high load effects due to the heavy non-existent merged axles. The auto-cleaning and automatic data quality control procedures successfully resolved most of these cases and reduced the differences to very reasonable 0.2 % below the final values for the bending moments (Figure 5) and to 3.4 % above the final values for shears forces (Figure 6).

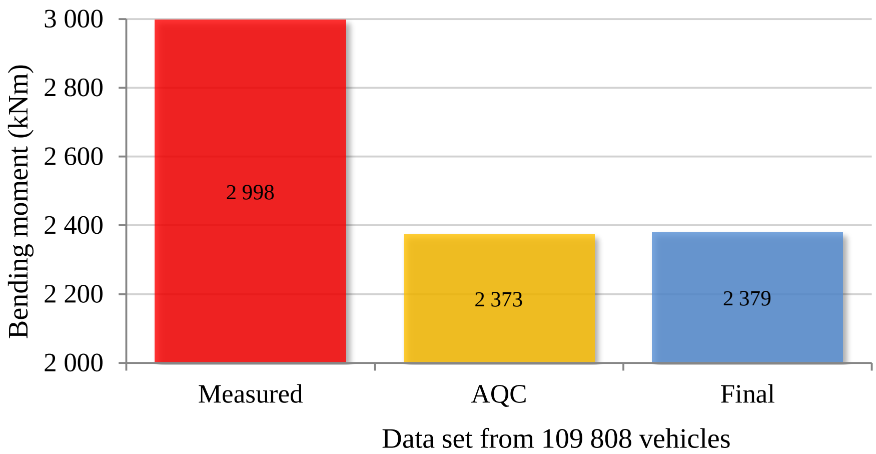

Figure 5 – Bridge B: calculated bending moments – 25 m span, all vehicles

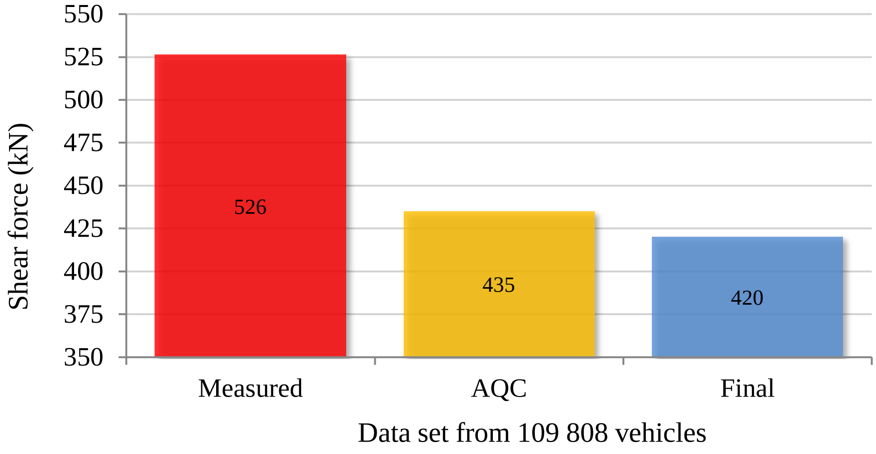

Figure 6 – Bridge B: calculated shear forces – 25 m span, all vehicles

The procedure was repeated for simply supported influence lines of five different lengths: 5, 15, 25, 35 and 45 m, and 3 sizes of datasets containing 20 000, 50 000 and all 109 808 vehicles (Figure 7).

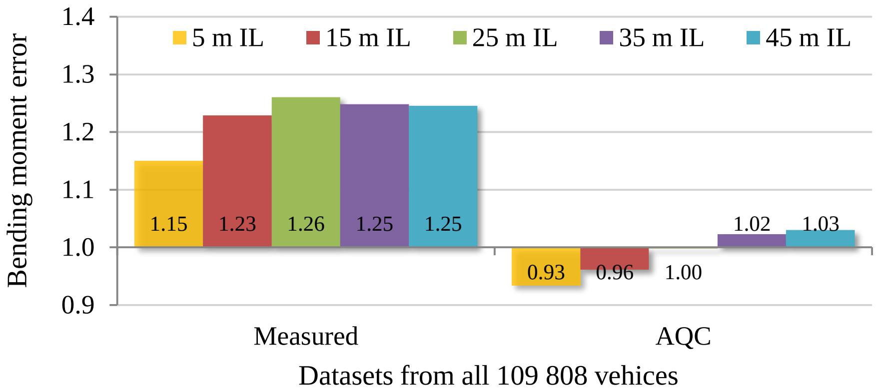

Figure 7 – Bridge B: bending moment errors for different quality datasets and different spans – mean values of 109 808-vehicle datasets

After applying the automatic quality control checks, the errors were similar to those from the Bridge A datasets. The error compared to the final values was between -7 % for the 5 m span, to +3 % for the 45 m span. While the 5-m and 15-m values were too low to be accepted without visual validation, the results for the other spans could be used for bridge data modelling without visually validating the heaviest vehicles.

5. Conclusions

Only two sets of data do not allow for reliable conclusions. Nevertheless, some recommendations can be given:

- Data quality verification must be applied. The auto-cleaning and automated quality checking procedures were effective. All auto-cleaned results were within a few percent of the final values, calculated from the highest quality datasets, in which all vehicles were visually verified. This suggests that at least the *automatic quality control (QC) procedure should be performed*. The results are still limited, but in both described cases, the load effects without applying the automatic QC procedure were overestimated for around 20 %.
- Comprehensive visual verification of results, as practiced in the past, is not needed. Depending on the required accuracy and reliability of the results, it is recommended to visually

validate the red-flagged vehicles. This will clarify the issues related with the most questionable records: the heaviest vehicles, which need to be approved, and the ones with real errors, which can be corrected and reweighed.
- Checking the orange-flagged and the green-flagged results will result in negligible changes with respect to calculated load effects. If high accuracy of the results is required, it may make sense to verify the heaviest (with respect to the measured strain) 1 % to 5 % of the orange-flagged results. However, this should be done only in exceptional cases.

6. Acknowledgment

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Session 7 : WIM Data for Infrastructure

Chair: Eugene Obrien (UCD, Ireland)

WIM DATA APPLICATIONS – PRACTICAL EXAMPLES FROM IRELAND





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Abstract

Transport Infrastructure Ireland (TII), the body responsible for the management and operation of the national road network in Ireland have recognised the value of collecting information on the weights of vehicles using their network. This paper provides an overview of a number of studies which utilised WIM data to examine the implications for bridges and pavements when considering potential changes to vehicle weight limits. An overview of a study specifically related to abnormal vehicle loading in Ireland is also presented, whereby tools are developed to improve procedures for the administration of permits for abnormally loaded vehicles on the Irish Major Inter-Urban Network. The findings of the studies presented herein have provided TII with invaluable insight into the effects of traffic on their infrastructure and have informed changes to regulations, notably when allowing a 2 t weight increase for 6-axle trucks.

Keywords: Weigh-in-Motion, Bridge Loading, Abnormal Loading, Pavement Damage.

Résumé

Transport Infrastructure Ireland (TII), le responsable pour la gestion et opération du réseau routière nationale en Irlande, a reconnu la valeur du recueil d'information des poids de véhicules dans le réseau. Cet article présente un résumé de quelques études qui utilisent les données de pesage en marche (WIM) à examiner les implications pour les ponts et chaussées en considèrent des changements potentiels aux limites de poids des véhicules. Cet article présente aussi un sommaire d'une étude par rapport à chargement anormal des véhicules en Irlande. Des outils dans le but d'améliorer les procédures de l'administration des permis des véhicules sur le réseau majeur inter urbain qui sont chargées anormalement, ont développés par cette étude. Les résultats de ces études qui sont présentées en cet article, ont fournis TII avec une compréhension invalable des effets du trafic sur l'infrastructure et ont avisés des changes aux règlements, notamment, pour une augmentation de poids de 2tonnes pout les camions de 6 essieux.

Mots-clés: Pesage-en-Marche, Chargement des Ponts, Chargement Anormal, Dégâts des Chaussées

1. Introduction

The efficient management of the Irish road network is of primary importance to ensure the ongoing functionality the network. With 5,300 km of national roads under its management, Transport Infrastructure Ireland (TII) is continually faced with challenging strategic decisions concerning the appropriate allocation of limited budgets. The level of traffic loading on pavements and structures is of major concern when considering the safety of structures and the deterioration of the road pavement.

The ability to monitor axle weights and gross weights of the vehicles using the network provides a useful insight into the actual traffic loading being experienced by bridges and pavements. This allows infrastructure managers to gain a deeper understanding of how the network is being used on a daily basis, ultimately facilitating more informed decision-making in relation to the management of the network.

TII have upgraded their traffic monitoring system in recent years and recognising the benefits of collecting information on vehicle loading, the upgrade included the installation of six permanent Weigh-in-Motion (WIM) sites along the national primary network, with accurate data collection beginning in 2014.

This paper presents an overview of a number of projects commissioned by TII (formerly the National Roads Authority, NRA, prior to 2015) and undertaken by Roughan & O'Donovan Innovative Solutions (ROD-IS), whereby WIM data was utilised to assist TII in understanding the effects of traffic loading on the network and the associated implications for bridges and pavements. TII have used the results of these studies to make recommendations on various regulations and procedures which govern allowable vehicle weights and dimensions on the Irish road network.

1.1 Use of WIM data in Ireland

The value of understanding the weights of the vehicles using the road network has been widely acknowledged in Ireland for a number of years. Prior to the commencement of accurate collection of WIM data in Ireland, in 2014, a number of representative WIM databases from outside of Ireland were utilised to examine the likely impacts of traffic on the bridges and pavements on the Irish national road network. WIM data from the UK, the Netherlands, Poland, the Czech Republic, Slovakia and Slovenia was used for a number of studies, before the collection of WIM data commenced in Ireland.

Figure 1 – Location of Six WIM Sites in Ireland

The six WIM sites in which were installed in Ireland are located on routes leading in and out of Dublin and their locations are shown in Figure 1. The WIM installations at each site consist of two piezo-polymer WIM sensors and one induction loop in every lane in each direction.

Calibration and accuracy classification of each of the sites was carried out on an annual basis in accordance with COST 323 (2003). A target accuracy class of C(15) or better was required before measured data was considered appropriate for use. The lane configuration details for each site are outlined in Table 1.

Table 1 – Irish WIM Sites

Site	Road Type	Lane Configuration
M1	Primary – Motorway	2 + 2
R147	Regional – Previously a primary route (N3). M3 motorway has now replaced this route.	2 + 2*
M4	Primary – Motorway	2 + 2
M7	Primary – Motorway	2 + 2
M11	Primary – Motorway	2 + 2

*Includes bus lane in each direction

2. Implications of Changing Weight Limits on 5 and 6-Axle Trucks

In 2011 the maximum allowable load for 5-axle trucks in Ireland was 42 t. This weight limit represented a temporary 2 t derogation from the actual weight limit for 5-axle trucks, which was set at 40 t. In addition, the maximum weight allowable for 6-axle trucks at the time was 44 t. The NRA commissioned a study to examine the implications of increasing the weight limit for 6-axle trucks from 44 t to 46 t and of making the 5-axle 42 t derogation permanent. The study involved two phases as detailed hereafter.

2.1 Preliminary Investigation

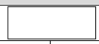
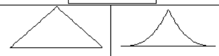
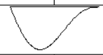
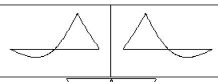
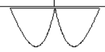
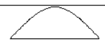
At the outset of the project, a preliminary investigation was carried out using a WIM database containing one month of truck data from the Netherlands. In order to classify typical truck configurations, a detailed statistical analysis was carried out of the 5-axle (40 t & 42 t) and 6-axle (44 t & 46 t) trucks contained in the database. This provided a vehicle template for the axle-configurations and axle-weights for 5-axle and 6-axle trucks which were subsequently used in the analysis.

In order to quantify the effects on general road bridges a number of influence lines were defined (Figure 2), which were deemed suitable to represent the critical global load effects for typical structures on the road network. These influence lines, which formed the basis of the re-calibration of the Eurocode LM1 load model (O'Connor et al. 2001), were analysed for bridge lengths ranging from 7.5 m to 200 m. These lengths represented the majority of Irish bridges.

The preliminary analysis involved running convoys of fully loaded 5-axle and 6-axle trucks across each of the influence lines to identify the critical load effects. The analysis considered 'jammed' (5 m gap between trucks) and 'free-flowing' (25 m gap) scenarios. For the jammed scenarios, no allowance for dynamic amplification was included whereas the free-flowing scenarios included a dynamic amplification factor applied to each of the axles. Once the critical load effects had been identified for each of the influence lines, these were then compared to the load effects induced by the following codified load models:

- HA design loading as per BD37/01 (Highways Agency, 2001a);
- LM1 design loading as per Eurocode 1 (NSAI, 2003);
- HA assessment loading as per BD21/01 (Highways Agency, 2001b).

The ratios between the critical load effects induced by the truck convoys and the load effects resulting from these codified load models were calculated for each influence line (a ratio greater than 1.0 indicates that the design/assessment load effects are exceeded). Examining these load effect ratios highlighted a number of critical influence lines which demonstrated high load effect ratios. Based on these load effect ratios and the structural forms of particular interest to the NRA a selection of influence lines (I0, I3, I4, I5 & I9) were chosen for more detailed analysis.

Influence Line Number	Representation	Description of the Influence Line
I0		Total load.
I1, I2		Maximum bending moment of a simply supported and double fixed[1] span, respectively.
I3		Maximum bending moment at the support of the former double fixed beam[1].
I4, I5		Shear force at the ends of simply supported bridge (assuming traffic flowing left to right).
I6		Moment at centre of central span in 3-span bridge with span ratios 0.7L:1.0L:0.7L (I6a) and 0.4L:1.0L:0.4L (I6b).
I7, I8		Minimum and maximum bending moment at mid-span of the first of two spans of a two span continuous beam.
I9		Continuous support moment of the former two span beam.
I10		Continuous support reaction of the former two span beam.

[1]with an inertia strongly varying between the mid-span and the ends

Figure 2 – Influence Lines Representing General Road Bridges

In addition to the analysis of general road bridges, the initial investigation also examined a variety of masonry arch geometries. Due to the geometric nature of arch bridges, a combination of axial and bending forces governs stability, making influence lines unsuitable for analysing them. As such, Archie-M software was used to carry out the analysis for masonry arches. The preliminary analysis of masonry arch bridges involved an assessment of the effect of the proposed increase in allowable vehicle load for 5 and 6-axle trucks, which was determined with respect to the ratio of maximum live load factor achievable at the ultimate limit state under each of the four truck silhouettes identified at the outset (5-axle 40/42 t & 6-axle 44/46 t) vs. that under the codified load model. It is noted that the only code load model analysed, and used for the purpose of comparison, relates to the assessment loading model prescribed by BD 21/01 (Highways Agency, 2001b) since it alone allows application of single and group axle loads for the assessment of arch bridges. In total, twenty masonry arch configurations were considered, with the geometries being based on particular structures on the Irish network. Single-span arches of 5, 10, 15 and 20 m were considered for five different geometric configurations:

- Circular arches (2 No.);
- Elliptical arches (2 No.);
- Three-centred arch (1 No.).

The results of this analysis showed that in a number of cases, the live load factor exceeded 1.0 and that tridem loading was dominant in these cases. As such, it was deemed appropriate to calculate the characteristic tridem weight for 5-axle and 6-axle trucks and to compare this to the characteristic tridem weight specified within BD21/01 (Highways Agency, 2001b). As such, arch bridges were considered further within the detailed analysis stage.

2.2 Detailed Analysis

While the preliminary investigation was useful for identifying critical structural forms to be examined it is noted that the absence of cars in the generated traffic mix could result in overly-conservative loading scenarios. The second stage involved more detailed and appropriate

simulations for the influence lines of particular interest (I0, I3, I4, I5 & I9). A summary of the analysis is provided in this section and further detail can be found in OBrien et al. (2012).
This analysis required another WIM database to be employed, this time from Poland, which had the significant advantage of containing both trucks and cars. Again, jammed and free-flowing scenarios were considered, and the maximum daily load effects induced by the traffic were calculated for each of these influence lines. Five different analyses were carried out in order to replicate the likely effects of the proposed changes to the regulations:

1. No modification to data: traffic used to calculate characteristic load effects;
2. Permit trucks removed and no change to trucks with 6 or less axles;
3. Permit trucks removed and any 5-axle truck deemed to be fully loaded, i.e., with weight in the range 36t to 42 t is increased to 42 t;
4. Permit trucks removed and any 5-axle or 6-axle truck with weight in the range 36 t to 44 t is replaced with a 6-axle truck with weight 44 t;
5. Permit trucks removed and any 5- or 6-axle truck with weight in the range 36 t to 46 t is replaced with a 6-axle 46 t truck.

Based on the maximum daily load effects calculated for each influence line, a statistical extrapolation was carried out to calculate the 1000-year characteristic load effect. This extrapolation used a Weibull distribution which was fitted to the maximum daily load effects and extrapolated to provide the 1 in 1000-year load effect, which could then be compared to the characteristic load effects induced by the code load models. Figure 3 shows a plot, on Gumbel probability paper, of daily maximum load effects with a Weibull distribution fitted to the data to extrapolate to find the load effect corresponding to a 1000-year return period.

The results of the analysis showed that congested traffic governed on the longer bridges (over 50m) while for short/medium-span bridges the free-flowing scenarios were generally more critical. In addition, the results for general road bridges showed that the currently used design/assessment codes were adequate to encompass the likely effects resulting from the proposed changes to the regulations.

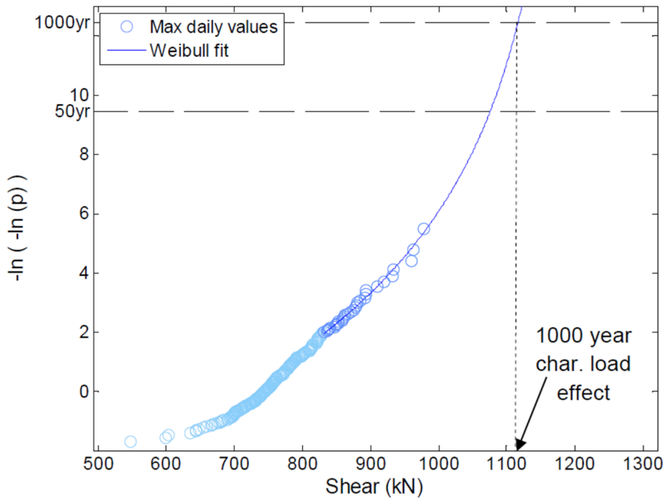


Figure 3 – Characteristic Load Effect Calculation

The analysis of masonry arches involved a similar procedure, however in this case, rather than extrapolating to find the characteristic load effect, it was more appropriate to carry out a probabilistic extrapolation to find the characteristic tridem weight for 5-axle and 6-axle trucks as the tridem weight was shown to be the critical factor governing the stability of the masonry arches. These characteristic tridems were then used to compare the live load factor achievable at ULS to that achievable using the characteristic tridem weight of BD21/01 for the twenty arch configurations examined in Phase 1. Results showed that the proposed changes were unlikely to be critical for masonry arches.

Finally, in order to consider the potential implications for pavement damage, a reasonably simple calculation was carried out to estimate the likely increase in pavement damage associated with the proposed weight limit increases. The fourth power law, often used to approximate pavement damage (Highways Research Board, 1962), was used in this calculation as per Equation 1.

$$PWDF = \sum_{i=0}^{n} ESAL_i^4 \tag{1}$$

Where *PWDF* is the Pavement Wear Damage Factor, *n* is the number of axles on the vehicle and $ESAL_i$ is the Equivalent Standard Axle Weight of axle *i* which can be calculated by dividing the weight of the axle being considered by a standard axle-weight 8 t (e.g. an axle-weight of 8 t has an *ESAL* = 1.0). In order to assess the implications for pavement damage, the *PWDF* was calculated for 1,000,000 t of freight using 40 t 5-axle vehicles, 42 t 5-axle vehicles or 46 t 6-axle vehicles. Carrying out this calculation showed that the derogation for 5-axle trucks, allowing a gross vehicle weight (GVW) of 42 t instead of 40 t, results in an increase of 11% in pavement damage, whereas carrying 46 t on 6-axles demonstrates 29% less damage than the 42 t 5-axle trucks. The overall results implied that increases in pavement damage were likely to be more significant than implications for bridges, and that a move towards 6-axle vehicles could reduce levels of pavement wear.

A number of similar studies were subsequently carried out by the NRA to examine the implications of increasing weight limits on other vehicle classes. The results of these studies were also used to inform proposed changes to legislation governing vehicle weights. These studies are not detailed in this paper; however Section 4 provides an overview of a similar study which was carried out to assist in the development of appropriate weight limits for non-regulated vehicles.

3. Improving the Administration of Permits for Abnormally Loaded Vehicles

Between 2012-2015 a study, commissioned by the NRA, aimed to develop tools to assist in the decision-making process for issuing permits for abnormally loaded vehicles while considering their effects on bridges on the Major Inter-Urban (MIU) routes (Corbally et al. 2017). Again, the work was carried out in two phases as outlined in the following sections.

3.1 Phase 1

Phase 1 of the project involved carrying out initial research and defining the appropriate assumptions which would be used within any analysis carried out in the project. A detailed review of the Eirspan database of Irish bridges was carried out to identify the types of bridges present on the MIU network. It was found that influence lines used in the previous study (Figure 2) were suitable to represent the majority of structures on the MIU network. Some additional influence lines, as described in Corbally et al. 2017, were also generated and included in the analysis to represent certain structures which weren't considered to be appropriately represented by those in Figure 2.

The next step was to identify and categorise typical vehicles being used to transport abnormal loads. Initially, records of permits previously granted by various local authorities were examined; however there was insufficient detail to accurately quantify the characteristics of the vehicles transporting abnormal loads. As such, a WIM database from the UK, containing approximately 2.8 million trucks was employed to examine abnormal vehicle characteristics. Eight weight classes were defined (50, 60, 70, 80, 90, 100, 125 and 150 t) and a detailed statistical analysis of the vehicles falling within each of the weight classes was carried out. On the basis of this analysis, the most common vehicle configuration in each weight class was extracted and used to develop a set of abnormal vehicle silhouettes. The axle weight distribution on these silhouettes was derived using an optimisation which aimed to ensure that the silhouettes, while representing actual vehicles, would induce greater load effects, considering all of the influence lines in Figure 2, than any other vehicle of the same configuration (Corbally et al. 2017). These silhouettes, Figure 4(a), represented the primary output of Phase 1.

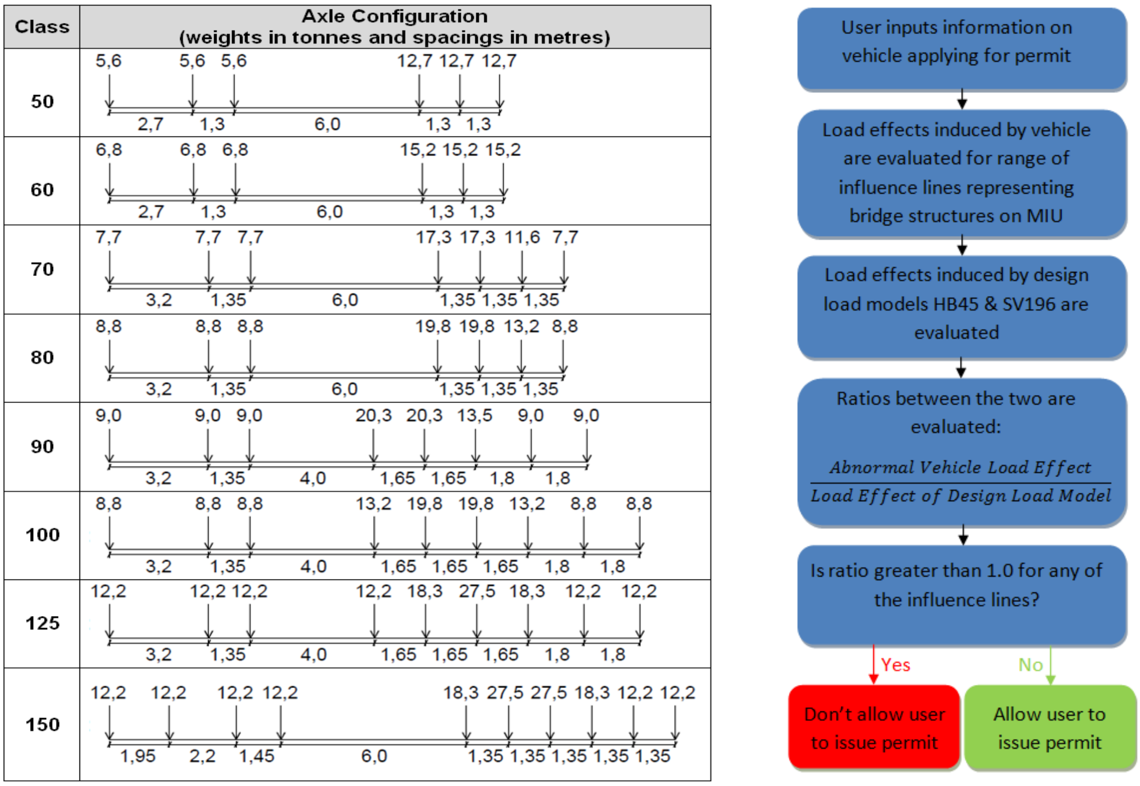
3.2 Phase 2

3.2.1 *Development of Permit Assessment Software Tool*

The second phase of the project focused primarily on the development of a basic software tool which could be used to consider the likely effects on bridges for an abnormal vehicle wishing to travel on the MIU network. This tool could be used by permit issuing authorities as part of their decision-making process for granting permits. This tool was developed within Microsoft Excel, with underlying computer code to carry out the analysis based on user inputs. Using a number of assumptions defined during Phase 1, the tool calculates load effects induced by a particular abnormal vehicle in 391 influence lines considered. These load effects are then compared to the design load effects for abnormal vehicles as defined within, BD37/01 (Highways Agency, 2001a) and EC1 (NSAI, 2003). The process by which the tool operates is outlined in Figure 4(b) and the user interface is shown in Figure 5. Further details on the tool can be found in Corbally et al. (2017).

3.2.2 *Comparison of WIM Data to Codified Abnormal Loading*

In addition to the development of the software tool discussed in the previous section, Phase 2 also utilised the UK WIM data to carry out an analysis of the load effects which the vehicles in the WIM database would induce in the influence lines outlined in Figure 2, for bridge lengths ranging from 2m-75m. This analysis was carried out to provide a general indication of the extremity of loading being experienced by in-service motorway bridges.



(a) (b)

Figure 4(a) – Representative Abnormal Vehicle Silhouettes; (b) Principle of Operation for Software Tool

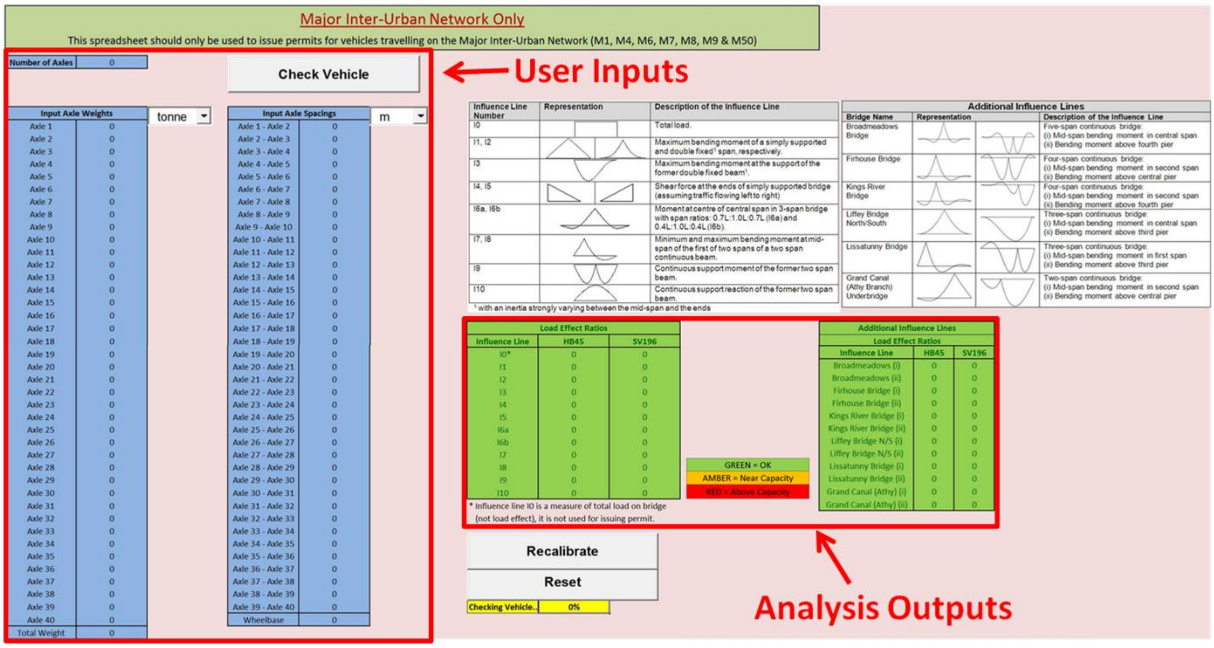
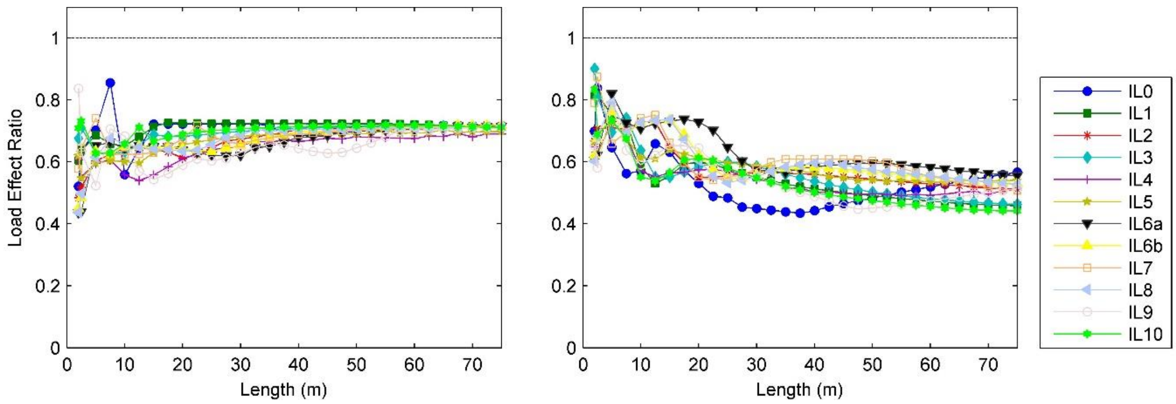


Figure 5 –Abnormal Vehicle Permit Software Tool

In order to quantify the severity of loading experienced, the load effects induced by the WIM vehicles was compared to the load effect calculated using the abnormal load models prescribed in bridge design codes in Ireland (HB45 load model as per BD37/01 & SV196 load model as per EC1). The results were expressed as Load Effect Ratios (*LER*) as per Figure 4(b), where a *LER* greater than 1.0 indicates a situation where the load effect induced by the WIM vehicles exceed the code load effect. The results of the analysis, shown in Figure 6, indicate that none of the calculated *LER*s exceed 1.0, providing some reassurance that the level of loading being experienced by typical motorway bridges is likely not exceeding what they should have been designed to withstand.



(a) **(b)**

Figure 6 – Ratio of Load Effects Induced by Actual Traffic vs. Design Load Models: (a) HB45 Load Model, (b) SV196 Load Model (Corbally et al. 2017)

A more elaborate description of the analysis can be found in Corbally et al. (2017), where it is noted that while providing some level of reassurance, it is not appropriate to draw any significant conclusions from such a high-level, simplistic analysis.

4. Weight Limits for non-Regulated Heavy Goods Vehicles

In 2015, after the collection of a year of WIM data from the six Irish sites, TII commissioned a project which aimed to identify suitable weight limits for 5-axle rigid vehicles along with 6-axle truck-trailer combinations of 4+2 & 3+3 axle configurations, as depicted in Figure 7. The 5-axle rigid trucks had previously not been covered by Irish regulations and as such a suitable GVW limit was required.

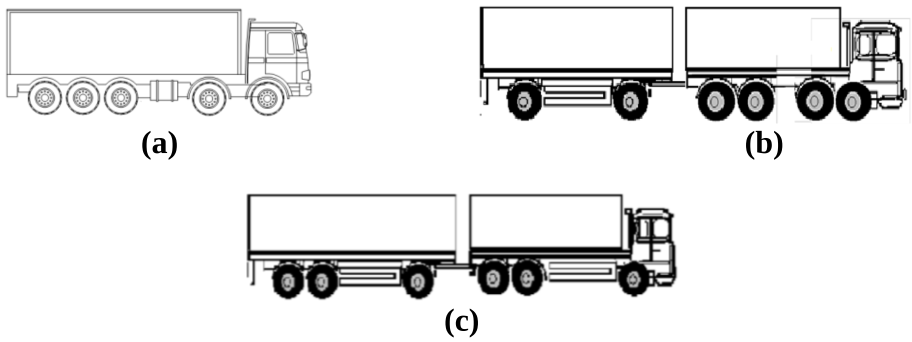


Figure 7 – Vehicle Configurations Examined: (a) 5-Axle Rigid (b) 4-Axle Truck Drawing 2-Axle Trailer (c) 3-Axle Appropriate Motor Vehicle Drawing 3-Axle Trailer

The two 6-axle configurations were examined to identify the impact of increasing their allowable GVW limit. This project represented the first application of measured WIM data from Ireland, providing a realistic insight into the impacts of Irish traffic on road infrastructure. Prior to the analysis, extensive checking and cleaning of the data was carried out to ensure that the results of the analysis would be as accurate as possible. One full year of records measured at the M4 WIM site was used to carry out the analysis, which involved carrying out long-run traffic simulations for varying levels of truck weights. Due to the fact that the proposed 5-axle rigid configurations had not been used in Ireland, Dutch WIM data was employed to examine the characteristics of these types of vehicles.

As with the previous projects, a preliminary simplified analysis was used to identify critical influence lines for general road bridges, for which the long run simulations were subsequently carried out. In addition, assessments of the effects on masonry arches and pavements were also carried out using the same approach as described in Section 2. The results of the simulations showed that the characteristic load effects induced by the current Irish traffic, without considering any changes to weight limits were unexpectedly high. It was found that there was a high level of overloading of vehicles on the Irish network; a problem which if not addressed could have major implications for the condition of bridges and pavements.

In order to identify a suitable GVW for 5-axle rigid trucks the WIM data was modified to introduce these new truck types into the traffic mix, while considering different potential weight limits. It was found that a maximum GVW of 36 t was acceptable. In addition, for the 6-axle truck configurations examined it was found that the limit on 3+3 axle-configuration could be increased by 2 t without resulting in any significant implications for bridges or pavements. Unfortunately, a scarcity of 4+2 type vehicles in the WIM data meant that no major conclusions could be drawn in relation to an appropriate weight limit for these trucks. The most significant finding of the study related to the high levels of overloading on the Irish road network, indicating that without improved enforcement procedures for vehicle weight limits, the effects of the traffic on Irish bridges and pavements are likely to be in excess of what had previously been assumed before WIM data collection had commenced in Ireland.

5. Conclusions

The collection of WIM data allows infrastructure managers to make more informed decisions in relation to the management and operation of their networks. This paper has presented a number of practical examples, from Ireland, of studies which utilised WIM data to allow TII to examine the implications of traffic loading on their bridges and pavements. In addition, the development of a series of abnormal vehicle silhouettes, along with a software tool, provides a means of considering bridges as part of the checking procedure when issuing permits for abnormally loaded vehicles wishing to travel on the Irish Major Inter-Urban Network. The results of the studies have been used to inform amendments to existing regulations governing vehicle weights while also assisting in the development of weight limit regulations for vehicle configurations not previously considered. The work presented represents a practical use of WIM data to allow the effects traffic on road infrastructure to be quantified as part of the decision-making process in relation to the operation of the network.

6. Acknowledgements

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IMPACT OF OVERLOADED VEHICLES ON ASPHALT PAVEMENT FATIGUE LIFE




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Abstract

The inoperability or absence of weighing stations in roads has resulted in uncontrolled load growth of commercial trucks. The lack of load control encourages the traffic of overloaded vehicles, and this practice is directly related to the premature deterioration of pavement structures. In the present study, traffic data obtained through a Weigh-in-motion (WIM) system installed in the Brazilian Federal Highway BR-381 were correlated with stresses observed in an experimental test site, where its service life reduction was simulated considering different load scenarios: (i) real traffic; (ii) traffic computing all overload loads up to 10% above the Brazilian legal limits (allowed tolerance by the Brazilian law); and (iii) traffic computing all loads up to the Brazilian legal limits. It was concluded that the practice of overloading on highways penalizes road traffic by accelerating pavement deterioration.

Keywords: Overloaded vehicles, traffic, weigh-in-motion, pavement.

Résumé

L'inopérabilité ou l'absence de stations de pesage sur les routes a entraîné une croissance incontrôlée de la charge des camions commerciaux. L'absence de contrôle de la charge encourage la circulation de véhicules surchargés et cette pratique est directement liée à la détérioration prématurée des structures de la chaussée. Dans l'étude ici présentée, les données de trafic obtenues à l'aide d'un système de pesage en marche (WIM) installé sur l'autoroute fédérale brésilienne BR-381 ont été corrélées aux contraintes observées sur un site d'essai expérimental, où sa réduction de durée de vie a été simulée selon différents scénarios de charge : (i) trafic réel; (ii) Toutes les surcharges des vehicules lourds sont limitées a 10% de la limite legal brésilienne (tolérance de surcharge autorisée par la loi du pays); et iii) le trafic pour tous les chargements jusqu'aux limites légales brésiliennes (sans tolérance de surcharge). Il a été conclu que la pratique de la surcharge sur les autoroutes pénalise la chaussée en accélérant sa déterioration.

Mots clés: Véhicules surchargés, circulation, système de pesage en marche, chaussées.

1. Introduction

One of the main targets when designing a pavement structure is to ensure that it withstands the traffic loads over its service life avoiding premature accumulated damage in terms of the main distresses, i.e., rutting, and fatigue cracking. According to Huang (1993), damages in the pavement structures occur mainly due to the application of high loads, or due to the large number of axle load repetitions. Therefore, it is essential to estimate correctly the damage caused by the different types of vehicles, in terms of axle configuration and loading magnitudes.

Currently, data collection and analysis of overloaded trucks on Brazilian highways are still very scarce. The lack of information can be related to the limited number of weighing stations, combined with their inadequate location (possible escape routes). Furthermore, most stations are usually open for short periods of the day since resources for weighing activities are often limited. Their restricted and predictable working hours induce the passage of overloaded vehicles at times when the weighing stations are not in operation, as previously reported by Bosso et al. (2018). In addition, the pavement design method considers the traffic limited to the maximum legal loads, not considering the presence of overloaded vehicles (Balbo, 2007). As a result, the traffic characterization usually does not represent the real scenario, increasing the pavement construction and rehabilitation costs.

The overloaded vehicles are one of the most important causes of pavement deterioration (Sadeghi and Fathali, 2007). This is especially critical in developing countries, where the traffic control is reduced. Cunagin et al. (1997) studied the correlation between enforcement efforts and the number of overloaded vehicles in Florida (USA), where two weight-enforcement stations and four possible evasion routes were monitored. In the study, the inspections efforts represented by the presence or absence of inspector on the evasion routes and the applicability of penalty charges when vehicles are overloading, increases from strategy A to D. As shown in Figure 1, the results demonstrated that the number of overloaded vehicles decreased considerably with the increase in inspection.

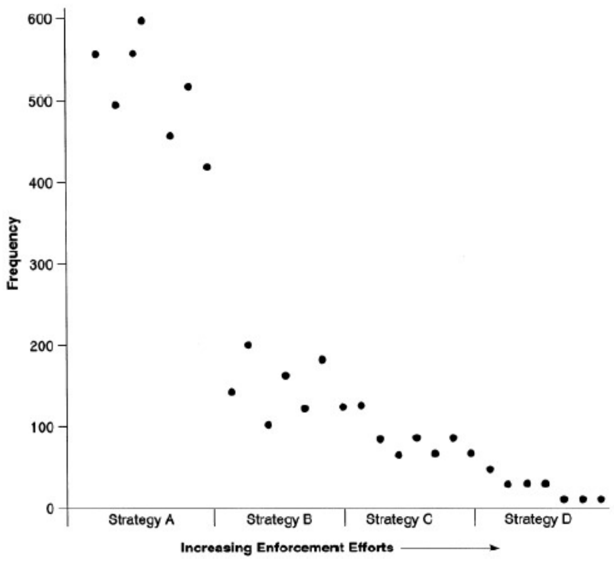

Figure 1 – Frequency of vehicles with at least 15% of load excess (Cunagin et al., 1997)

The method for determining how much damage a particular axle causes has its origins in the American Association of State Highway Official (AASHO) road test conducted in the 1950s. The research found that the relationship between axle load and the pavement damage is a power function with an average exponent of 4 (Highway Research Board, 1962), result from different exponent values (varied from about 3.6 to 4.6) for different pavement types and different wear mechanisms. Later, other studies also confirmed this relationship (Pinto and Preussler, 2002; Atkinson et al., 2006; Dawson, 2008).

2. Experimental test site

The experimental test section monitored in this study was constructed in December 2014 in a high traffic Brazilian federal highway (BR-381). This highway connects São Paulo and Belo Horizonte, two major metropolitan areas in Brazil. The 100 m-length segment was constructed with 120 mm-thick dense hot mix asphalt (HMA) as wearing course and crushed stone as its base course material (Figure 2).

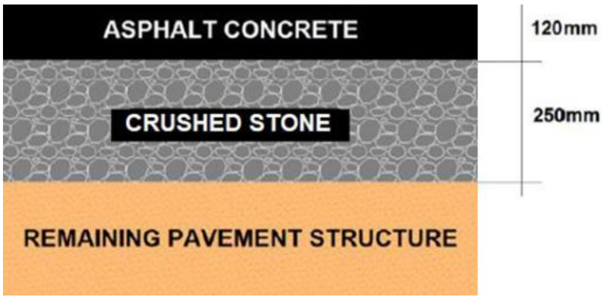

Figure 2 – Schematic section of the experimental test site

The materials linear elastic properties are presented in Table 1. Andrade (2017) presents further details on the materials characterization, construction monitoring, functional performance monitoring data and structural aspects of the experimental test section.

Table 1 – Pavement structure adopted on the experimental test site

Layer	Thickness (mm)	Modulus (MPa)	Poisson’s ratio
AC	120	5004	0.35
Crushed stone	250	115	0.45
Remaining pavement structure	–	145	0.45

The experimental test site was monitored for 25 months, when it reached the end of its service life and had to be reconstructed. This paper focuses on the effect of overloading on the fatigue cracking evaluation of the surface asphalt layer.

3. Weigh-in-motion system and the traffic data

According to Austroads (2000), a WIM system is a device capable of measuring the dynamic weight of a moving vehicle's axle to estimate its respective static weight per axle. The use of WIM is indicated as an alternative to monitor the actual loads applied to the pavement, allowing the identification of overloaded vehicles. Many countries use WIM technologies for overload screening, and new studies are being developed for using high speed weigh-in-motion (HS-WIM) system for direct enforcement of overloads (Cottineau et al., 2016; Gajda et al., 2016; Doupal et al., 2016).

The data used in the present study were obtained from a high-speed WIM system installed in both lanes of the Brazilian highway BR-381. The system meets the requirements for a Type I WIM scale as defined in ASTM E1318-09 (2009). The main components of the equipment are: (i) inductive loops for detecting vehicle; (ii) sensitive piezoelectric sensors for the measurement of the stresses caused by the vehicles wheels; (iii) thermocouple temperatures sensors PT-100 installed into the pavement; (iv) electric wires; and (v) cables. In each line, the configuration adopted was L-P-L-P (loop-piezo-loop-piezo) system.

The use of WIM systems allows a more accurate analysis of the traffic characteristics, as the data acquisition system continually registers the vehicles that travel directly on the road, storing a set of information about its characteristics. The raw data, the data processing, and the output results are illustrated in Figure 3.

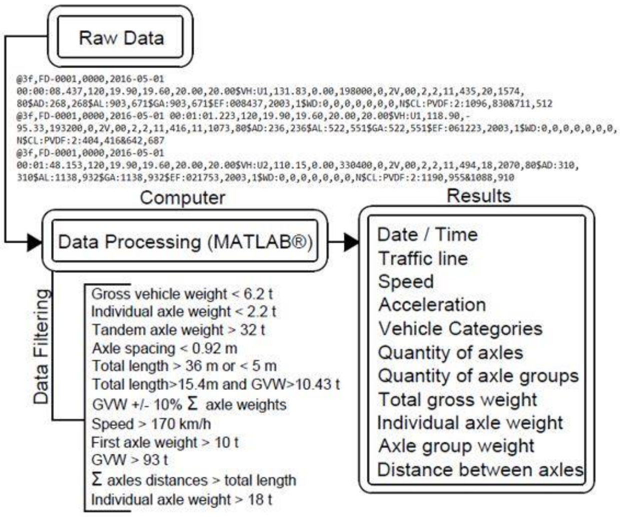

Figure 3 – Data acquisition and processing

The vehicles classification was carried out according to the guidelines presented by the Brazilian National Department for Transportation Infrastructure, DNIT (2012), considering the number and distance between the axles registered. The schematic figures of the 15 most frequent categories in this highway, representing more than 95% of the commercial vehicles, are presented in Figure 4.

The overloaded vehicles significantly affect the fatigue life of pavement structure, as well as the potential rutting, and have a negative impact on the number of accidents. Thus, in order to guarantee the integrity of the structures for their design period and the road safety, since the 1960s, weights and dimensions limits were established for the circulation of vehicles on Brazilian roads.

The Brazilian tolerance over the legal load limit for the gross vehicle weight is 5% and for the axles is 10%. The current weight limits in Brazil establish: (i) maximum total gross weight depending on the vehicle class; and (ii) maximum axle weight depending on its configuration (6, 10, 17 and 25.5t for single axles with single wheels, single axle with dual wheels, tandem axles, and tridem axles, respectively). Overloading occurs when at least one axle presents load higher than the legal limits. The percentage of overloaded vehicles determined in this study is presented in Figure 5. It can be noticed that overloading is more critical for the categories 3I1/3DI/33D/3C3/3JD, 3LD/3DT and 3M6/3Q6.

Figure 4 – Most frequent categories in BR-381

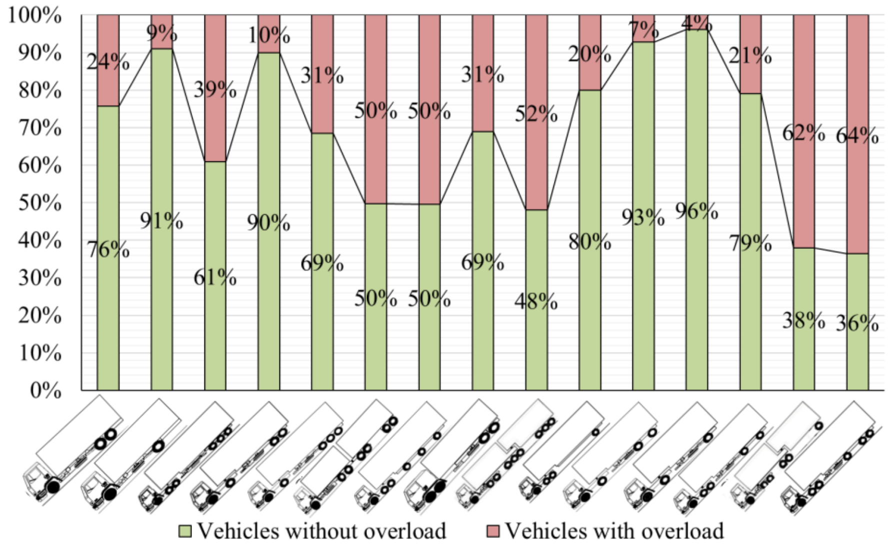

Figure 5 – Percentage of overloaded vehicles per category

The monitoring of load distributions practiced in BR-381 demonstrates the relevance of evaluating the effect of the overload observed in the reduction of pavement life. Based on the WIM system data, the effect of all different types of vehicles was converted into a standard axle resulting in the equivalent single axle load (ESALs), by the American Association of State Highway and Transportation Officials (AASHTO).

Figures 6 shows the accumulated traffic. Three different load scenarios were considered: (i) actual traffic considering the measured WIM loads; (ii) traffic considering Brazilian tolerance, where all axles that exceeded the legal load limits were replaced by the Brazilian maximum legal load axle value with the tolerance of 10%; and (iii) legal load traffic, where all axles that exceeded the maximum legal load were replaced by their maximum legal value. The system collected the data between September 2015 and December 2017. Therefore, between December 2014 and August 2015 (period in which the experimental test site was already constructed) an extrapolation of WIM data was made.

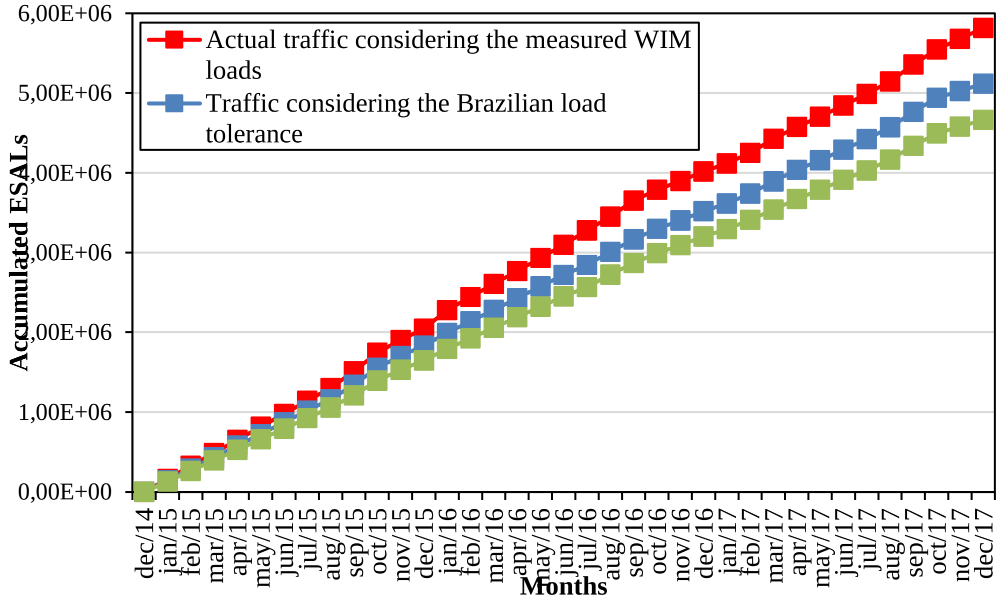

Figure 6 – Accumulated number of ESALs

Figures 6 shows the effect of overloaded vehicles on the accumulated number of ESALs, which is responsible for the increase of 24% when comparing with all commercial traffic considering legal load per axle. When comparing the actual traffic considering the WIM data scenario to the traffic considering the Brazilian load tolerance, this difference decreases to 14%, but it is still relevant. It is worth saying that, as the overloading was eliminated from the previous analysis, more truck trips would be needed to move the same volume of freight, resulting in numbers of ESALs even greater than the presented for the traffic considering the Brazilian tolerance and legal load traffic.

4. Cracked area evolution in the experimental test site

The asphalt road pavement is a structure designed to support the stresses and strains induced by the vehicle loading to which the asphalt layer is submitted during the design period. Over time, the vehicles repeated solicitations deteriorate the pavement structure, and the main distresses that occur in Brazilian asphalt pavements are rutting and the fatigue cracking. In the present research, the effect of overloads is approached considering only the fatigue cracking by means of predictive models available in the literature.

The fatigue phenomenon is described as the deterioration of the asphalt material when it is repeatedly requested, resulting in the development and propagation of cracks in the asphalt layer. In well-designed pavement structures, the distresses are observed in proportions that compromise the structure close to its design life period. However, early distresses are common, and might be related to design errors, e.g., the one related to the difficulty of predicting the actual traffic that will pass through the pavement.

In order to analyze the influence of overloading on the pavement structure response, regarding the structural performance of the experimental test site, the occurrence of cracks was monitored through detailed visual survey according to DNIT-PRO 008/2003 (2003), as can be observed in Figures 7. The figure also shows the 20% limit used by different predictive models.

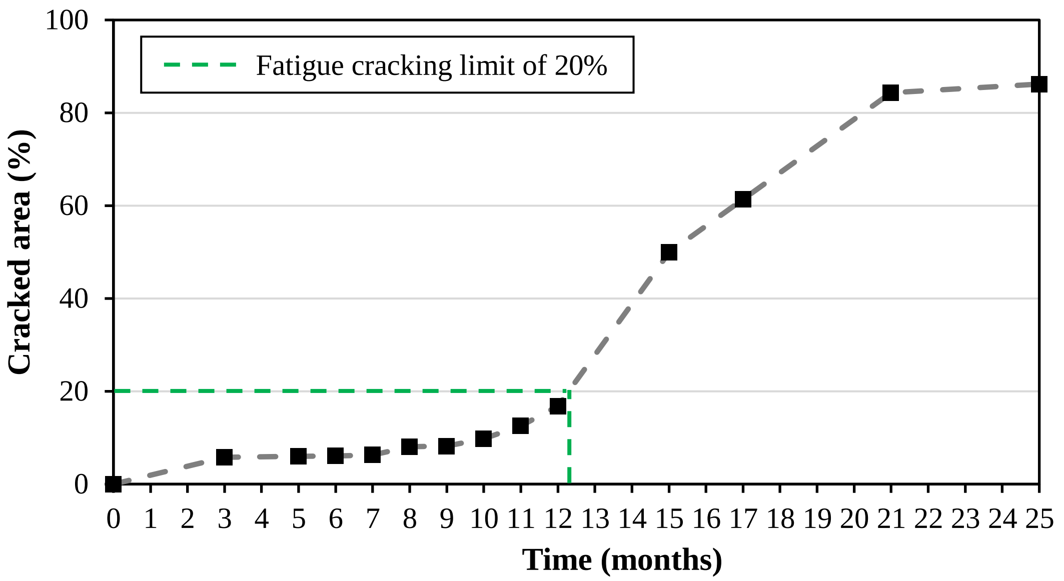

Figure 7 – Cracked area evolution as a function of time

Microcracks were observed already in the first three months of operation of the experimental test section. The percentage of the cracked area increased slightly during the initial seven months (up to July 2015), a fact that can be attributed to the dry season. With the onset of the rainy season, the percentage of cracked area increased exponentially, reaching the limit of 20% with a little more than 12 months old, indicative of structural impairment according to the DNIT (Brazilian Federal Highway Administration).

5. Pavements life reduction simulation considering different load scenarios

The analysis of fatigue damage caused by the overloaded vehicles was based on the mechanistic-empirical approach. There are different methods and models for estimating the fatigue life of a pavement structure. Many models relate the tensile strain at the bottom of the asphalt layer with the number of ESALs, until a certain cracked area, as shown in Equation 1. Table 2 shows some coefficients of traditional fatigue models for the asphalt concrete coating.

$$N = k \times \left(\frac{1}{\varepsilon_t}\right)^n \qquad (1)$$

Where: N is the number of accumulated ESALs to fatigue failure;
ε_t is the horizontal tensile strain at the bottom of the asphalt layer;
k and n are fitting coefficients.

Table 2 – Fitting coefficients of fatigue models

Reference	k	n
Verstraeten, Veverka and Francken (1982)	4.92E-14	4.76
Powell et al. (1984)	1.66E-10	4.32
Thompson (1987)	5.00E-06	3.00

There are also models that include the material property. The empirical-mechanistic method of the AASHTO method, known as the Mechanistic-Empirical Pavement Design Guide

(MEPDG), suggests the use of Equation 2, and the most used coefficients are from Shell Oil (1980) and the Asphalt Institute (1982), shown in Table 3.

$$N = Ck_1 \times \left(\frac{1}{\varepsilon_t}\right)^{k_2} \times \left(\frac{1}{E}\right)^{k_3} \quad (2)$$

Where: N is the number of accumulated ESALs to fatigue failure;
ε_t is the horizontal tensile strain at the bottom of the asphalt layer;
E is the stiffness modulus of the asphalt mixture at the intermediate temperature;
k_1, k_2 and k_3 are fitting coefficients;
C is a correction factor influenced by the volume of binder and voids for the AI model; and binder volume, asphalt layer thickness and asphalt binder penetration index for the Shell Oil model.

Table 3 – Fitting coefficients of fatigue models

Reference	k_1	k_2	k_3
Asphalt Institute (1982)	7.96×10^{-2}	3.291	0.854
Shell Oil (1980)	1.00	5.000	1.400

From the methodology of the Asphalt Institute (AI), the number of ESALs for fatigue failure for the structure of the experimental test section was 1.93×10^6. Further details on the parameters used in the calculations are presented by Bessa (2017). Comparing the ESALs obtained with the accumulated traffic considering the different load scenarios, values presented in Figure 6, it is possible to verify the pavement service life reduction in relation to the estimated fatigue ESALs (Figure 8). A similar analysis can be performed with the real ESALs of fatigue observed in the field, where it is known that the structure reached the limit of 20% of the cracked area with 2.01×10^6 (Figure 9).

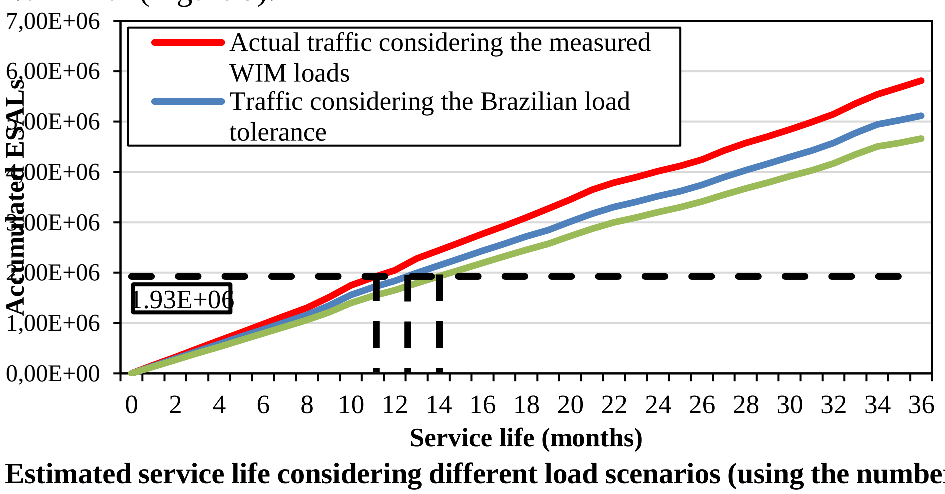

Figure 8 – Estimated service life considering different load scenarios (using the number of ESALs of the AASHTO's method, and fatigue ESALs calculated by Asphalt Institute model)

In order to summarize the results of the overload practices on BR-381, the pavement life reduction compared to the ideal scenario (vehicles traveling with loads up to the legal limit) is presented in Table 4. It is noticed that the practice of overloading penalizes the pavement by accelerating the degradation of its structure, which consequently will result in a greater number of interventions, requiring more investments than initially planned.

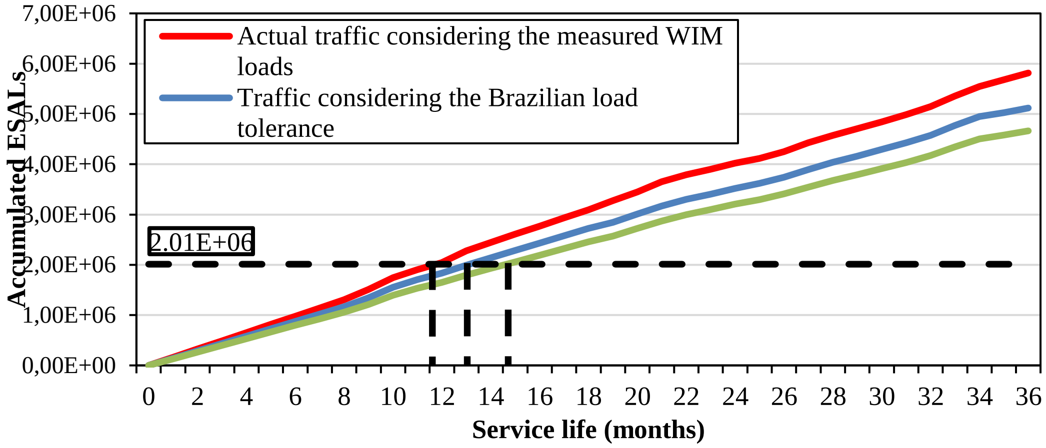

Figure 9 – Observed service life considering different load scenarios (using the number of ESALs of the AASHTO's method, and fatigue ESALs observed in field, considering the limit of 20% of the cracked area)

Table 4 – Pavement life reduction

Fatigue number of ESALs	Life reduction considering load traffic up to 10% tolerance in relation to legal load traffic	Life reduction considering real traffic in relation to legal load traffic
1.93E+06 (Asphalt Institute, 1982)	10.2%	21.2%
2.01E+06 (actual observed in the field)	10.5%	23.0%

6. Conclusions

The main objective of this study was to evaluate the service life reduction of the pavement structure due to the presence of overloaded vehicles. Initially, based on the analysis of the data recorded by the WIM system, it was possible to quantify the overload. Then, an experimental test site was monitored regarding their fatigue cracking distress (by means of cracked area on the surface layer). The monitored segment was constructed with crushed stone as the base course material. Usually, unbound base layers provide higher deflections to the pavement structure, which affects the performance of the pavement in terms of cracking initiation and propagation. Therefore, considering the traffic conditions of the BR-381, the early occurrence of cracks in this segment was already expected. From the traffic analysis between September 2015 and December 2017, comparing the real traffic and the legal load traffic, it was possible to verify that the presence of overloaded vehicles resulted in considerable differences in the number accumulated of ESALs, being responsible for 24% increase. Finally, the fatigue life calculated considering the Asphalt Institute model, and the fatigue life observed in the field, were compared to the three different load scenarios (real traffic, traffic in the Brazilian load tolerance, and legal load traffic). The pavement's service life reduction due to the overloaded vehicles varies from 10.2% to 23.0%. As the fatigue life calculated and observed in the field were similar, for the flexible pavement analyzed, the classic fatigue life model correlated well with field results in terms of cracked area, despite the fast increase in the cracked area.

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IMPACTS OF THE LACK OF WEIGHT ENFORCEMENT ON MAINTENANCE COSTS OF THE BRAZILIAN ROADWAY NETWORK





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Abstract
Recently, Brazil has been subject to a suspension of all weight enforcement activities on the Federal roadway network. Since road transportation is responsible for more than 60% of the freight transportation in this country, this fact has important consequences, mainly to the conservation state of road infrastructure. In this paper, a brief timeline of the state of weigh assessment in Brazil is presented, and data from different sources within the Brazilian Department of Terrestrial Infrastructure (DNIT) is analyzed in order to estimate the impact of such lack of enforcement on overloading practices and on the cost of maintenance. Data from a single section over one year after the suspension of enforcement has shown that the percentage of overloaded vehicles grew by 87% in this period. Various measurements in different states also show that in approximately the same time span an average of 34% of vehicles weighed on Federal highways were overweight. Such increase on the percentage of overloaded vehicles was found to produce an average increase of 19% on yearly maintenance costs, and extreme scenarios were found to increase maintenance costs by 38%.

Keywords: weigh in motion; enforcement; maintenance costs.

Résumé
Récemment, le Brésil a été suspendu ses activités de contrôle du poids sur le réseau routier fédéral. Considérant que le transport routier est responsable de plus de 60% du transport de marchandises dans ce pays, cela a des conséquences importantes, principalement sur l'état de conservation des infrastructures routières. Dans cet article, un bref historique de l'état de l'évaluation de la pesée au Brésil est présenté et des données provenant de différentes sources au sein du Département de l'Infrastructure Terrestre (DNIT) du Brésilien sont analysées afin d'estimer l'impact de l'absence du contrôle des poids lourd sur le coût de l'entretien des réseaux national. Les données correspondent d'une seule section plus d'un an après la suspension de l'application de la loi ont montré que le pourcentage de véhicules surchargés avait augmenté de 87% au cours de cette période. Diverses mesures effectuées dans différents États du pays montrent également qu'environ la même période, environ 34% des véhicules pesant sur les autoroutes fédérales étaient en surpoids. Il a été constaté que cette augmentation du pourcentage de véhicules surchargés entraînait une augmentation moyenne de 19% des dépenses d'entretien annuels, et que des scénarios extrêmes entraînaient une augmentation des dépenses d'entretien environ de 38%.

Mots-clés: pesage en marche; mise en vigueur; coûts des infrastructures.

1. Introduction

In Brazil, more than 60% of the national freight transportation is carried through the roadway system. As such, road transportation has a major significance to the economic scenario in Brazil, which makes the conservation of Federal highways one of the pillars of economic growth for the Ministry of Transportation. It has been shown that one of the main factors related to pavement degradation is the existence of overloaded vehicles (Jacob and Beaumelle, 2010), since the pavement is designed considering a specific weight per axle and overloads usually mean an excess beyond the design weight.

The entity responsible for weight enforcement in Federal roadways in Brazil is the National Department of Transportation Infrastructure (DNIT). This department has several programs to control freight transportation within the Federal network, including the National Weighing Plan, the National Traffic Counting Plan (PNCT) and the National Electronic Control of Velocity Plan (PNCV). However, in 2013, DNIT has been subjected to a public civil action filed by the Public Prosecutor's Office (MPT). As a result of this action, all weight control activities being carried by DNIT were paralyzed, which caused overload enforcement in Federal roadways in Brazil to be completely suspended.

Even though enforcement activities were suspended, infrastructure already existent still collected weight data of all vehicles in transit on some sections of the Federal road network through weigh-in-motion (WIM) systems. This allowed a unique view of the impact of the lack of weight enforcement on the characteristics of the traffic in these regions. The comparison of weight data before and after the suspension gives an idea of the impact of this lack of enforcement in the behavior of freight transport companies, as well as an estimate of the increase in maintenance costs due to this excess weight.

In this paper, firstly, a brief timeline of the state of weight enforcement in Brazil is presented. After this, the data collected through a few years both with and without weight enforcement is presented. With this data, an increase in the percentage of overloaded freight vehicles is observed, which allows for a simulation of the increase in maintenance costs due to a few different scenarios. Lastly, the analysis of this data gives an estimate of the economic impacts of the lack of weight enforcement in Brazil.

2. The state of weight enforcement in Brazil

Since the arrival of the automobilist industry in Brazil in the 50s, the government has invested widely on the development of the Federal roadway network. As a part of this, the Institute of Roadway Research (IPR) developed a standard method for the design of flexible pavement structures. This method aims to provide a given service life for the road corresponding to a certain number of repetitions of a standard axle weight. Because of this, in order to guarantee the specified service life of the roadways, it is fundamental to enforce proper weight limits to freight transport vehicles.

Since the decade of 1960 weight control was carried in the Brazilian roadway network. In the early stages, static scales were used, with dynamic scales also entering operation around 1980. It was only in 2006, though, that the knowledge of studies exposing the impact of excess weight on the service life of roads motivated a heavier investment on weight control programs in Brazil. This triggered an upgrade on infrastructure and on the control parameters measured by weighing stations in Brazil.

In 2013, however, the Public Prosecutor's Office (MPT) filed a civil action against the National Department of Transportation Infrastructure (DNIT), disputing the practices used when hiring weight station personnel back in 2007. As a result of this action, in June 2014, the DNIT was sentenced to not prorogate the contracts of weight station workers or hire new personnel with the same process, which effectively put a stop to the operation of all weight control stations on the Federal network.

Since then, aiming at restoring weight enforcement activities in the Federal network, the DNIT has worked with other public entities in order to make viable the implantation of a new model of Integrated Automatized Enforcement Station (PIAF) which would increase the number of parameters collected from vehicles and allow the reestablishment of weight control on Federal highways with an automatized process, that would minimize the need for human interaction on weighing stations. Although significant progress was made in this direction, though, no weight enforcement stations entered operation.

As a result of this process, after a wide period of weight control in Federal highways, freight transporters in Brazil have not been subject to any weight control enforcement for approximately four years. This situation allows for an analysis with real data of the impact of such lack of enforcement on overloading practices by road users.

3. Available data and methodology

For the analysis proposed in this paper, a few sources provided data of weight overload of freight vehicles in Federal highways both before and after the suspension of weight enforcement in 2014. This section shows the data collected in this study and the significance of each sample for the analysis carried out in this paper.

3.1 Vehicular Weighing Stations (PPV)

Firstly, data from Vehicular Weighing Stations (PPV) are given for the year of 2012, while weight enforcement was still active. This data includes, for a few weighing stations, the average number of weighed vehicles and number of overweight infractions per day. This resulted in an average per station of 734 weighed vehicles and 48 infractions per day, which means an average of 6,5% of weighed vehicles were found to be overweight. Table 1 shows the average number of weighed vehicles and overweight infractions for 24 stations analyzed in this period. It can also be observed that, in this period, the maximum observed daily infraction percentage was of 12%. This data, which was provided by DNIT in the form of daily reports, shows the behavior of freight transporters regarding overloading in a year where weight control was still active.

3.2 National Traffic Counting Plan (PNCT)

Another source that provided data for this analysis was the National Traffic Counting Plan (PNCT). This program provided infrastructure in many sections of the Federal roadway network, with the main purpose of describing the nature of the traffic in Brazilian highways. In order to do this, the equipment utilized in this program is capable of counting, measuring, weighing and classifying all passing vehicles into the HDM model classes. The weigh data collected with this program does not provide enough precision for direct enforcement (the maximum allowed error is 30%), but it does serve as means of characterizing the traffic in these sections.

Table 1 – Daily averages of weighed vehicles and overweight infractions over the year of 2012 for Brazilian Vehicular Weighing Stations (PPV)

Station	# of weighed vehicles	# of overweight infractions	% of overloaded vehicles	Station	# of weighed vehicles	# of overweight infractions	% of overloaded vehicles
501	1600	68	4%	1003	307	24	3%
601	312	27	5%	1005	197	8	3%
602	595	57	3%	1014	540	64	3%
603	1113	90	5%	1101	1287	87	7%
604	614	51	3%	1102	861	83	12%
606	316	33	5%	1201	1030	79	9%
607	247	38	6%	1301	733	52	7%
608	124	5	3%	1604	318	22	4%
609	679	29	3%	1608	641	52	2%
610	715	33	1%	1701	871	60	3%
611	1731	50	3%	1702	967	49	1%
612	836	64	4%	1703	1026	42	3%

In order to analyze the difference in overloading percentages with this program's data, various samples of one month of data were collected in a few different states. The selected data covers a span of a few months between December 2014 and November 2015. Table 2 shows the months of data and percentage of overloaded vehicles for each of the samples obtained from this program. It's possible to observe that the average of overloaded vehicles in this sample is significantly higher than of the previous sample, collected when weight enforcement was still active. In this case, the average percentage of overloaded vehicles observed was of 34%. The most extreme sample in this case was in the month of May 2015 in the state of Bahia, which resulted in 53% of overloaded freight vehicles in transit.

Table 2 – Monthly sample collected from the National Traffic Counting Plan (PNCT) with percentage of overloaded vehicles over a few months on the years of 2014 and 2015.

State	Month	% of overloaded vehicles
São Paulo (SP)	December 2014	49%
Minas Gerais (MG)	December 2014	37%
Santa Catarina (SC)	January 2015	17%
Bahia (BA)	May 2015	53%
Mato Grosso (MT)	September 2015	18%
Rio Grande do Sul (RS)	November 2015	25%
Average		34%

Besides collecting the percentage of overloaded trucks, this program also measures the vehicles and counts the type and number of axles, determining also the occurrence of overweight per axle. This data allows for classification of the traffic in these sites according to HDM classes, and will be used as input for road deterioration models when estimating the increase in maintenance costs on section 5 au-dessous.

3.3 Track Control Station (ECP)

As a prototype for the research of WIM technologies, a test site was built in the city of Araranguá/SC, south of Brazil. Part of this test site is a Track Control Station (ECP), which weighs passing vehicles with various WIM systems with enough precision to serve as pre-selection for weight enforcement on the planned Integrated Automatized Enforcement Stations (PIAFs). This station is in continuous operation since November 2014, and continues to collect data in this road section.

Given the continuity of this station's operation, it is possible to analyze the differences in freight transport behavior in a wide period after the suspension of weight enforcement in 2014. To observe this effect, data was summarized from this station for three different periods: the month of November 2014, the period between January and June 2015, and the period between July 2015 and January 2016.

Table 3 – Number of weighed vehicles, overweight infractions and percentage of overloaded vehicles for three different timespans on the Track Control Station at the Araranguá/SC WIM test site.

Period	# of weighed vehicles	# of overweight infractions	% of overloaded vehicles
Nov/2014	37118	8862	24%
Jan – Jun/2015	66631	25194	38%
Jul/2015 – Jan/2016	127165	57094	45%

As well as measuring the percentage of overweight infractions in this test site, this station also produce axle data usable to classify vehicles into HDM classes. This was used in order to confirm the characteristics found on the PNCT sample.

4. Impacts on user behavior

While intuitive, many studies have confirmed that that the lack of enforcement on weigh control in highways leads to an increase in the occurrence of overweight infractions (Coiro and Arriola, 2016; Han et al., 2012; Jacob and Cottineau, 2016). In fact, this same effect can be observed in the data collected in the Brazilian road network. While measures from 2012, a year in which enforcement was still active, showed an average of 6.5% of overweight infractions, measures after the suspension of enforcement in 2014 have shown widely varying values, with an extreme monthly average of 53%, as presented in Table 2. In order to show this evolution, Figure 1 presents a timeline of the overweight percentage from the different sources presented on section 3 above.

While data from the PPV and PNCT programs vary widely in terms of placement of the observed sections and infrastructure utilized for the measurements, the ECP covers the timespan of approximately one year measuring the same road section with the same equipment. This way, the characteristics of the surrounding area and the nature of the measured traffic can be considered approximately constant.

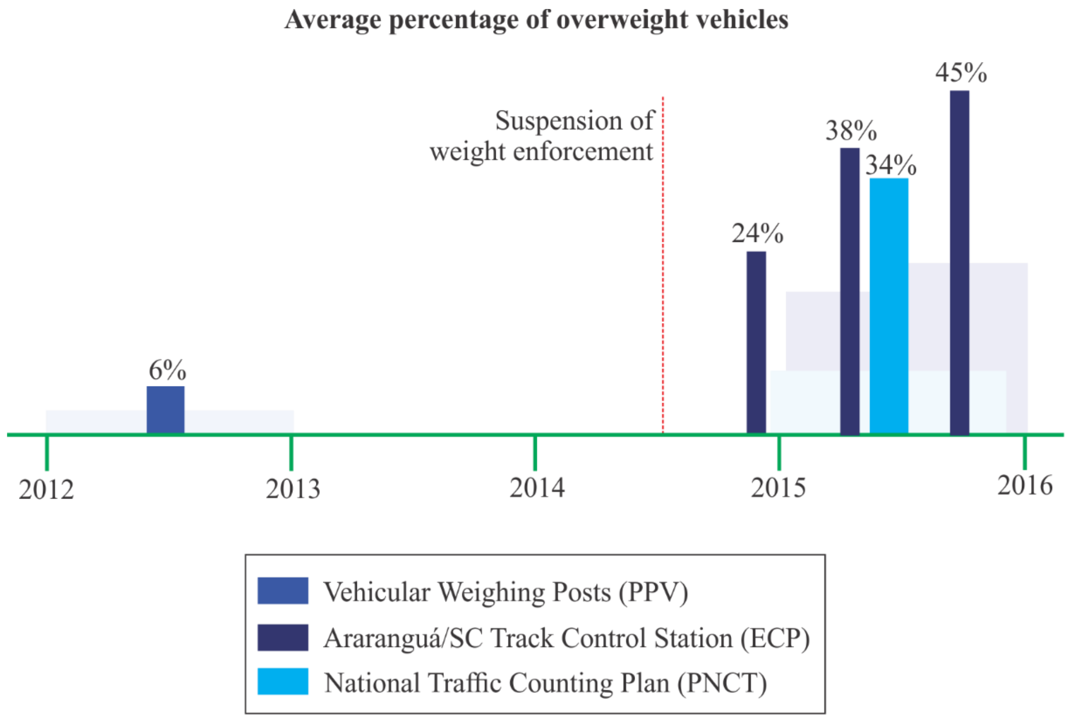

Figure 1 - Timeline of average weight overload percentages on different timespans from three different sources in the Brazilian Federal roadway network

The data presented in Table 3 and Figure 1 shows that, after weight enforcement stopped, in a span of one year (November 2014 to January 2016), the average number of overweight vehicles in the particular section of the ECP have increased by more than 87%. This observation confirms the premise in the studies cited above, in that the lack of enforcement did in fact increase the average number of overweight vehicles in transit.

5. Increase in maintenance costs

In Brazil, just as in other countries, freight vehicle overweight is pointed out as a cause of the low durability of roads (Confederação Nacional dos Transportes, 2017). In fact, international research also shows that vehicles in transit with excess weight are a significant factor to reduce the durability of roads due to the increased displacements and cracks produced in the pavement. (Jacob and Beaumelle, 2010).

In order to estimate the economic impact of an increase in the number of overweight vehicles on the cost of maintenance of the Federal highways in Brazil, the HDM-4 computational tool was used (Kerali, 2000). This software implements a deterioration model that considers the characteristics of a roadway, the traffic data and the maintenance policies in order to determine the cost of maintenance over time. In this study, the same model was applied into three different scenarios, all with the same road and traffic characteristics, varying only on the percentage of overweight vehicles, in order to analyze the estimated impact of this variable on roads with Brazilian characteristics.

The first scenario, used as reference, assumes an overweight vehicle percentage of 6%, which is considered as a normal case during weight enforcement. The second scenario considers the increase in overweight vehicle percentage due to the lack of enforcement, assumed as 34%. In the third scenario, the most extreme case encountered in the analyzed data is considered, where the overweight vehicle percentage is assumed as 53%, which is the same percentage presented in the PNCT data for the state of Bahia (Table 2).

5.1 Road and Traffic characteristics

In all cases, the same pavement and traffic characteristics are provided. These characteristics were chosen to represent the majority of the Brazilian roadways and, where possible, real data from traffic measurements were used.

The input data for the road model is as follows: with regards to the road section, the road is a simple two-lane road, with free flow, primary road class, with an asphalt surface pavement with granular base; the width of the track is 7.2 m, with 2.5 m shoulders; the total length of the analyzed segment is 1 km. With regards to the quality of the structure: the quality of the construction, structural condition and texture of the pavement are considered as "reasonable". As for surface degradation: cracked areas and the appearance of potholes will be considered, and the wheel path is considered with poor condition. The geometry of the sample road is considered as slightly curved and undulated.

For the traffic data, the conditions are as follows: the annual daily average traffic is considered as 26,000 vehicles per day; the annual growth rate is 1.5% for passenger cars and 4.5% for freight vehicles. The classes of the vehicles and fleet composition are the same as observed in the PNCT data (presented in subsection 3.2). The weight per axle is considered as equal to the legal limit, plus the average excess percentage observed in PNCT data. The year of start of operations for this model is 2016, and the analysis considered a period of 24 years.

5.2 Estimated costs of maintenance

The policies for maintenance are based on thresholds set on the International Roughness Index (IRI), the percentage of cracked area in the pavement and the number of potholes per km. The analysis with the deterioration models, given such policies, will provide the estimated timeline of maintenance for the roadway in study. The given official estimated costs for maintenance interventions for the month of January 2016, are the ones presented in Table 4.

Table 4 – Estimated costs in US$ for maintenance interventions on Brazilian Federal highways in January 2016.

Intervention	Estimated Cost
Reconstruction of the pavement	$ 332,682.51 / km
Rehabilitation of the pavement surface	$ 11.99 / m²
Pavement milling	$ 12.88 / m²
Pothole covering	$ 44.37 / m²
Routine maintenance (per year)	$ 3,186.29 / km

5.3 Results of the simulation

The HDM-4 tool allocates the given costs for every time an intervention is triggered based on the given criteria. With this, the cost of each scenario can be compared during the service life of the reference segment. This analysis shows an increase in the total maintenance costs due to the increase in the number of overloaded vehicles. From these values, the average yearly maintenance cost can be determined for each scenario, which in turn determines the percentage of cost increase in each scenario with increasing overloaded vehicle percentages.

At the first scenario, with 6% of overloaded trucks, the average annual maintenance cost per km is of approximately R$ 73,000.00 ($19.600,00). The second scenario, that considers the average number of overloaded vehicles (34%), resulted in an average cost of R$ 86.000,00 ($23,100.00). The extreme case of 53% of overloaded vehicles resulted in an approximate R$ 100,000.00 ($26,900.00) yearly per km. These values are also shown in Figure 2, which shows that the first scenario of 34% of overload caused an increase of 19% of the yearly cost of maintenance, and the extreme case of 53% an increase of 38%.

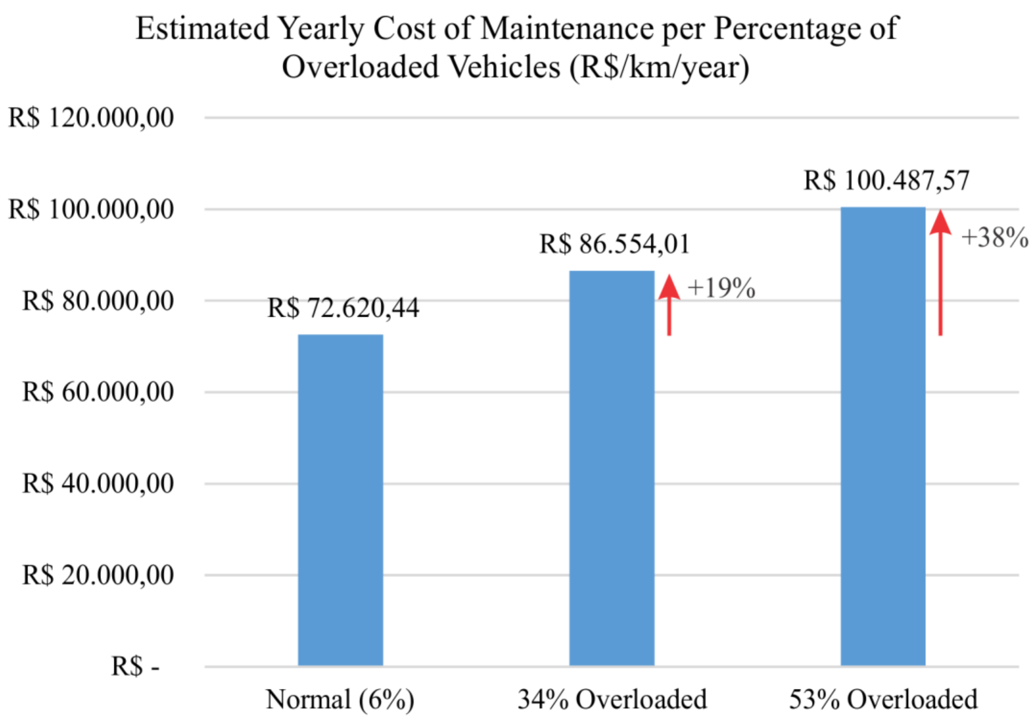

Figure 2 – Average yearly cost of maintenance per percentage of overloaded vehicles

6. Conclusions

In the past few years, Brazil was subject to a suspension of all enforcement related to overweight in Federal roads. In order to evaluate the economic impact of such lack enforcement, this study collected data from various sources in order to characterize the traffic in such highways and estimate an increase in overloading practice and maintenance costs due to the lack of control in Federal highways. Such data was presented as obtained from three different sources: the Vehicular Weighing Plan (PPV), the National Traffic Counting Plan (PNCT) and the Track Control Station (ECP) at the WIM test site in Araranguá/SC.

An increase of more than 87% on the percentage of overloaded vehicles was observed in a span of one year after the suspension of weight enforcement, on a single constantly monitored road section. Analysis of different samples from road sections around the country also estimated that, during the year of 2015, approximately 34% of vehicles were found to be overloaded. The most extreme case observed was the month of May 2015 on the state of Bahia, where 53% of the weighed vehicles were overweight.

The characterization of the traffic on Federal highways and the road structure, obtained from the same data sources as the weigh data, was used with the HDM-4 road degradation model in order to estimate the timeline of necessary maintenance interventions in a period of 24 years. The model was used in three different scenarios, varying only on the percentage of overloaded vehicles between 6% (reference), 34% and 53%. Official cost estimates of maintenance interventions were used in order to calculate the maintenance costs of all scenarios.

It was found that the scenario with 6% of overweight vehicles, the reference case, resulted in an average yearly maintenance cost per km of approximately R$ 73,000.00 ($19.600,00). The second scenario, with 34% of overload, resulted in an average of R$ 86.000,00 ($23,100.00) per km per year, an increase of 19%. The third scenario, with 53% of overloaded vehicles, resulted in approximately R$ 100,000.00 ($26,900.00) per km per year, which represents an increase of 38% from the reference case. Such results point to the significant impact of the lack of weight enforcement on maintenance costs of Federal highways in Brazil.

7. Acknowledgements

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ROAD PRESERVATION USING DIRECT ENFORCEMENT WIM: IN-THE-FIELD EXPERIENCE FROM THE RUSSIAN FEDERATION



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Abstract

Local authorities often face reality when comparing the projected and true road lifetime. The projected lifetime is based on a qualified estimation of traffic intensity and structure, yet it is very complicated to predict the number of overloaded trucks. Lack of this information is critical because these vehicles are the ones causing the most road damage.

The paper shows a real-world experience that one of the most accurate ways of determining the level of road damage is using WIM systems to measure Equivalent Single Axle Loads (ESALs) - the real cumulative road load. Results show that by installing a CAMEA WIM direct enforcement system in the Russian Federation together with fining the overloading violators can increase road lifetime significantly.

Keywords: WIM, direct enforcement, weight enforcement, vehicle overloading, LEF, LEFs, ESAL, ESALs, road preservation, road lifetime, cumulative load.

Résumé

Les authorités locales font souvent face à la réalité quant aux différences entre la durée de vie envisagée et la durée de vie réelle . Pour déterminer la durée de vie d'une route, une estimation qualifiée de l'intensité et de la structure du trafic est utilisé. Cependant, prévoir le nombre de véhicules surchargés est très compliqué (difficile). La manque d'information aggrave cette situation car ce sont ces véhicules qui causent pour la plupart la dégradation des routes.

Le document indique que l'utilisation des systèmes WIM est l'une des manières les plus précises d'estimation du niveau de la dégradation des routes qui permet de mesurer la charge cumulative des routes réelle - Equivalent Single Axle Loads (ESALs). Les résultats indiquent que l'installation du système CAMEA WIM avec le contrôle automatisé en Russie et avec une amende pour des véhicules surchargés pourrait prolonger la durée de vie des routes de façon significative.

Mots-clés: WIM, contrôle automatisé, contrôle de poids, véhicules surchargés, LEF, LEFs, ESAL, ESALs, conservation de routes, durée de vie des routes, charge cumulative.

1. WIM Site and Data

1.1 WIM Site

The Weigh-In-Motion (WIM) site analyzed in this paper is placed in the Russian Federation (RF). The road where the WIM sensors are installed has 2 traffic lanes of the same traffic direction. Prior to the WIM system installation, the right traffic lane was completely reconstructed to comply with the COST 323 recommendation for road class I Excellent. Left traffic lane conditions were already compliant.

Both traffic lanes were equipped with the weighing sensors to avoid the possibility of bypassing the WIM system. The WIM sensor setup of each traffic lane was of standard design:

- 2 rows of Kistler Lineas weighing sensors (4 sensors in total).
- 2 inductive loops.
- 2 sensors for wheel position measurement.

1.2 Accuracy

The WIM station was designed to comply with RF authorities' requirements (Приказ №1014 2012):

- ± 5% gross weight error.
- ± 10% axle weight error.
- Speed range: 20 to 140 km/h

The WIM system was installed in July 2017 and calibrated in August 2017. Both traffic lanes were calibrated using a preloaded vehicle. Vehicle wheel weights were used for calibration. Gross weight standard deviation below 2 % was observed for both WIM traffic lanes.

1.3 Data for the Analysis

This paper analyses the right (slow) traffic lane. Most of the heavy traffic was present in this traffic lane. Bypassing the WIM was not possible because of the installation of the sensors in both lanes and the truck drivers were not tempted to use the left (fast) traffic lane.

Five months of traffic data were processed for the right traffic lane starting with the first month after calibration (September 2017) and ending with January 2018. Data prior to September 2017 could not be used because the system was not fully calibrated. Data after January 2018 were not used because an increased error of the WIM system was detected for the right traffic lane. The inspection on site later revealed that the right traffic lane was significantly damaged by highly overloaded vehicles.

A reference site was used to place the results into a broader context. This reference WIM is placed in the Czech Republic near Brno on a first-class road leading from Vienna (AT) to Brno (CZ). The Brno site road is of similar type of use and it also has 2 traffic lanes.

2. WIM Site Traffic Analysis and WIM System Impact

For the purpose of the analysis the vehicles are divided into to 3 categories:

- Personal cars (< 3.5 tons).
- Small trucks and light delivery vehicles (3.5 - 10 tons).
- Heavy vehicles (> 10 tons).

2.1 Traffic Composition

The counts of vehicles are listed in the table below. Two approaches were used to estimate year counts. First estimation is based on the average of all available data (5-month). Second estimation is based only on data from September 2017. In this second estimation the traffic which was not influenced by WIM system installation is predicted.

Table 1 – Traffic composition at WIM site

Category	9/2017	10/2017	11/2017	12/2017	1/2018	Year estimate	Year estimate (Sept.)
< 3.5 tons	188980	183565	193736	187251	179973	2240412	2267760
3.5 - 10 tons	18146	16519	15428	13861	10430	178522	217752
> 10 tons	42831	37461	32080	32753	27786	414986	513972
Total	249957	237545	241244	233865	218189	2833920	2999484

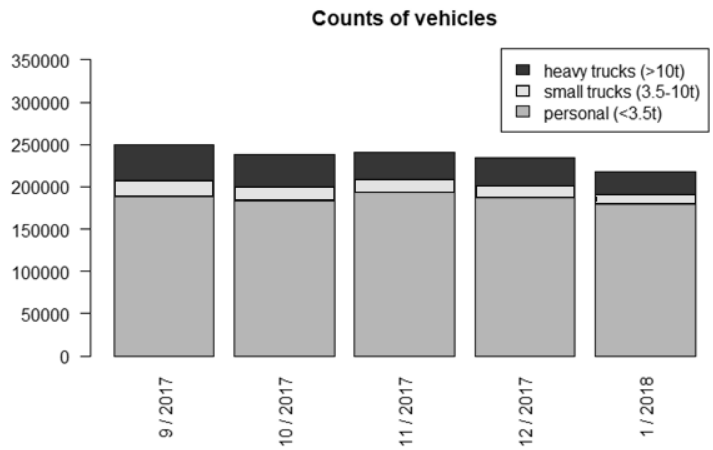

Figure 1 – Traffic composition at WIM site

Observed traffic density in the right WIM traffic lane is comparable to other localities which have a road of similar type and count of traffic lanes. In fact, the values are lower than values observed at the reference site. Please see table below.

Table 2 – RF WIM site compared to Brno (CZE) WIM site

Category	< 3.5 tons	3.5 - 10 tons	> 10 tons	Total
WIM site in Brno 2016	4214113	209470	694207	5117790
WIM site in RF	2267760	217752	513972	2999484

The WIM system is not necessary to obtain similar traffic statistics. Any traffic counter which is able of a basic classification of the vehicles into several categories could be used for the task. For example, inductive loops (see TLS 2012), radars, laser scanners (e.g. SICK TIC product family or similar) or axle counters will produce similar values with respect to its classification accuracy and used classification schemes.

The observed vehicle counts and the traffic composition are not uncommon. The data does not suggest any extensive road load.

2.2 Cumulative Load

The cumulative load is defined as a sum of loads of all vehicles in a particular category and time period. The cumulative loads for observed time periods are listed in the table below.

Table 3 – Cumulative load at WIM site in kilotons

Category	9/2017	10/2017	11/2017	12/2017	1/2018	Year estimate	Year estimate (Sept)
	[kt]	[kt]	[kt]	[kt]	[kt]	[kt]	[kt]
$<$ 3.5 tons	300.9	286.3	280.3	270.2	258.5	3350.6	3610.3
3.5 - 10 tons	101.8	92.4	86.7	78.0	58.4	1001.5	1221.1
$>$ 10 tons	1480.6	1113.4	850.7	890.5	820.6	12374.1	17767.6
Total	1883.3	1492.1	1217.7	1238.7	1137.5	16726.2	22599.0
Avg. for $>$ 10 tons vehicle	0.0346	0.0297	0.0265	0.0272	0.0295	0.0298	0.0346

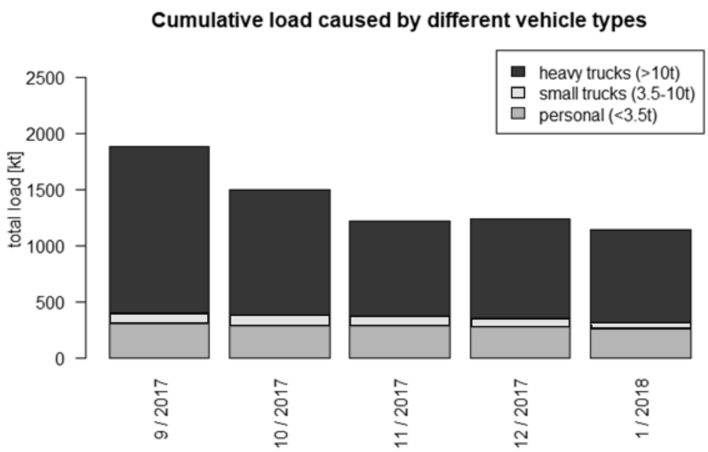

Figure 2 - Cumulative load at WIM site

Depending on the used year estimate the average weight of a heavy truck is 29.8 tons using the average estimate or 34.6 tons using the September estimate. Those values are significantly higher compared to the Brno WIM site. The 2016 average was 25.5 tons for the Brno WIM site.

This data cannot be accurately obtained by any traffic counters. Common approach used for traffic counters is to assign the expected average weight to each vehicle category. For axle-counting classifiers, the count of axles could be considered. The cumulative load is then computed as combination of the category counts and those expected weights. Such estimation is inaccurate and can be subjected to high errors in situations where true vehicle weights are not consistent with the expected average weights.

Cumulative load data compared to the reference WIM site indicates that road utilization is significantly higher than the common average. It is not clear, though, how much this average load is dangerous for the road lifetime.

The cumulative load decrease observed in the time period from September to November 2017 is caused by the start of repressive actions towards the overloaded drivers in October 2017. The decrease is more significant using the ESALs approach discussed in the next chapter.

2.3 ESALs Analysis

2.3.1 ESALs

According to the ASTM E1318 (2009):

- Equivalent Single-Axle Loads (ESALs) are the cumulative number of applications of the chosen standard single-axle load that will have an equivalent effect on pavement serviceability as all applications of various axle loads and types by vehicles in a mixed-traffic stream.
- Load Equivalence Factor (LEF) is a numerical factor that defines the number of applications of a chosen standard axle load and type that is expected to cause damage to a specified pavement structure.

The LEFs were derived by the American Association of State Highway and Transportation Officials (AASHTO) based on "Highway Research Board Special Report 61E" (1962). For purpose of AASHTO design guides the 18000lb. (8164.7kg) single-axle equivalent load is used.

According to ASTM E1318 (2009) AASHTO ESALs are determined by calculating and summing the LEF for each axle set on all vehicles in a measured or assumed mixed-traffic stream according to its axle type (single, tandem, or triple) and magnitude of load for a defined pavement structure and terminal serviceability.

According to "Evaluation of AASHO Interim Guides for Design of Pavement Structures" (1972) the LEF for an axle and flexible pavements can be calculated by solving the following equations using U.S. customary units (please see the references for more details):

$$LEF_{L_i,n} = \left[\frac{(L_i + n)^{4.79}}{(18 + 1)^{4.79}}\right]\left[\frac{10^{G_t/\beta_{18,1}}}{\left(10^{G_t/\beta_{L_i,n}}\right)\left(n^{4.331}\right)}\right] \tag{1}$$

$$\beta_{L_i,n} = 0.40 + \frac{0.081(L_i + n)^{3.23}}{(\overline{SN} + 1)^{5.19}(n^{3.23})} \tag{2}$$

$$\beta_{18,1} = 0.40 + \frac{1094}{(\overline{SN} + 1)^{5.19}} \tag{3}$$

$$G_t = log\left[\frac{4.2 - p_t}{4.2 - 1.5}\right] \tag{4}$$

where:

$LEF_{L_i,n}$ is the Load Equivalence Factor of load L_i on type n axle.
L_i is load i on the axle set under consideration (lb./1000).
n is an axle-type code (1 for single-axle, 2 for tandem-axle, 3 for a triple-axle set).
p_t is the terminal serviceability index.
$\overline{SN}$ is the structural number of the pavement structure.

Because the exact road parameters are not known, the following assumptions were used to evaluate the data from the WIM site:

- terminal serviceability index $p_t = 2.5$

- structural number of the pavement structure $\overline{SN} = 3.0$

2.3.2 ESALs at the WIM Site

The ESALs evaluation results for the WIM site are listed in the table below. Other than heavy vehicles have negligible effect on the ESALs computation results.

Table 4 – ESALs at the WIM site

Category	9/2017	10/2017	11/2017	12/2017	1/2018	Year estimate	Year estimate (Sept 2018)
	ESALs	ESALs	ESALs	ESALs	ESALs	ESALs	ESALs
< 3.5 tons	96	144	134	119	114	1457	1152
3.5 - 10 tons	1061	1622	1382	1257	1163	15564	12732
> 10 tons	652688	410819	133435	84326	105225	3327583	7832256
Total	653845	412585	134951	85702	106502	3344604	7846140
Avg. for > 10 ton vehicles	15.2	11.0	4.2	2.6	3.8	8.0	15.2

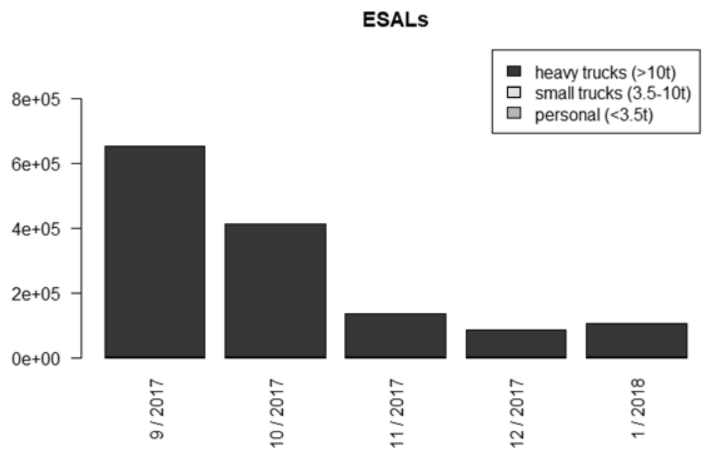

Figure 3 – ESALs at the WIM site

The amount of ESALs recoded at the WIM site is extremely high. The reference site values are multiple times lower compared to these results. This data suggests a presence of highly overloaded vehicles on the WIM site. The ESALS value decrease observed in the time period from September to November 2017 is clearly visible and corresponds to drivers' reactions to the start of repressive actions. The values are decreasing towards the values observed on the reference site.

Table 5 – ESALs at the WIM site compared to reference site

	Year estimate	Year estimate (Sept)	Brno reference site
Total year ESALs (> 10 tons vehicle)	3327583	7832256	1415874
ESALs/vehicle (> 10 tons vehicle)	8.0	15.2	2.0

Only a WIM system is able of such ESALs analysis because of actually measured axle weights. No traffic counter is able to provide such data for analysis nor provide data for weight enforcement.

2.4 Vehicle Overloading on Site and Caused Road Damage

2.4.1 Overloading

ESALs values are indicating high count of overloaded vehicles on site. Counts of overloaded vehicles are listed in the table below. Please note that truck weight limits differ in both countries.

Table 6 – Counts of overloaded heavy vehicles

	9/2017	10/2017	11/2017	12/2017	1/2018
WIM site in RF	19318	13732	4036	3890	5246
	45.1 %	36.7 %	12.6 %	11.9 %	18.9 %
WIM site in Brno 2016 (full year)	10037				
	1.4 %				

Amount of vehicle overloading is more significant for the road damage than the count of overloaded vehicles. The trucks on the site were overloaded to extreme values. It was common for an overloaded truck to be loaded almost to a triple of the allowed values. Such a truck could easily produce more than 200 ESALs.

Table 7 – Examples of common overloaded vehicles

Vehicle type	Axle 1	Axle 2	Axle 3	Axle 4	Axle 5	Axle 6	GW	ESALs
	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	
	11801	10862	28320	28130			79113	309
	11410	10150	28613	27411			77584	297
	11007	10068	28476	27494			77045	296
	7786	26847	26301	19194	15541	17024	112693	291
	10979	24449	25175	19797	19166	20649	120215	273
	9833	10659	28066	26946			75504	273
	11442	25139	24661	20678	16846	20424	119190	270
	9446	24910	26278	18972	18278	18202	116086	270

For comparison, a standard loaded 5 axle semitrailer truck (40 tons) would produce approximately 4.15 ESALs depending on the axle weight distribution.

2.4.2 Road Damage by Overloaded Vehicles

Increased error of WIM measurements was observed in January 2018. Inspection done on site revealed road damage: The road surface had locally decreased by several centimeters in a 2x2 m area prior to the Kistler sensors and ruts were formed at the WIM site. Based on this initial inspection full road analysis has been performed using a specialized laser measurement device. The results show approximately 6 to 12mm ruts in the right traffic lane. These measurements were also confirmed by manual measurements.

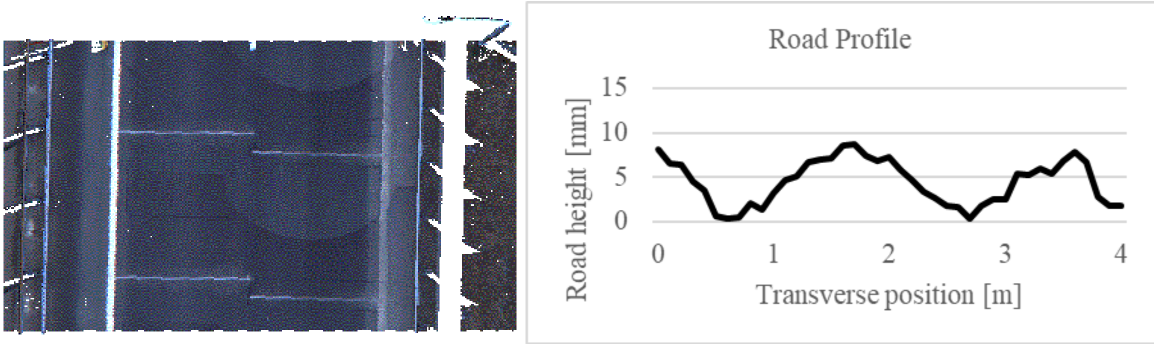

Figure 4 – Road 3D model and average road profile at sensors' location (right lane)

The ruts were formed in a 6-month interval after road renovation. In the last two months of the period the ESALs for heavy vehicles decreased to an average value of 3.2. That is almost a 5 times lower value compared to the value 15.2 observed in September. The road would have been preserved for several years if such correct truck loading was enforced sooner and long-term.

For comparison, the reference WIM site in Brno has served for 5 years and the formed ruts did not exceed 5 mm. Of course, this comparison is inaccurate because the road construction differs, but the higher lifetime of the Brno road is mainly a result of significantly lower overload counts and lower truck loading.

3. Conclusion

The road lifetime is, among other factors, subjected to the amount of vehicle loading. The AASHO ESALs methodology could be approximated to a so called 4^{th} power law. The axle loaded to a double of a standard weight will cause a 16 times higher damage to the road. This principle tells us that truck overloading can reduce the road lifetime multiple times. Fatal consequences of such truck overloading were observed at the WIM site analyzed in this paper. The road was damaged in a 6 month period because of extremely overloaded vehicles. The road lifetime could be at least 5 times longer with correctly loaded truck traffic.

Simple or advanced traffic counters are able of a precise analysis of the traffic flow composition. Unfortunately, only limited information on possible road wear can be obtained by classification and vehicle counting. The vehicle classifiers are only able of cumulative weight estimation based on an expected average weight for each vehicle class. Such estimation is inaccurate and can be subjected to high errors in situations where the true vehicle weights are not consistent with the expected average weights. Only a WIM system can provide accurate weight information. This weight information can be used for:

- Planning of the new road capacity with respect to known load of the current infrastructure.
- Estimation of the current road conditions and the end of the road lifetime.
- Enforcement of the correct truck loading to significantly increase road lifetime.

The violation volume and violation overweight values have been significantly reduced in a few months. The road load measured in ESALs has dropped almost 5 times in a short time period. This data proofs that the WIM system used for direct enforcement or preselection enforcement can significantly extend lifetime of the road. Correctly loaded road requires less maintenance and longer renovation periods. All these factors significantly reduce the costs of traffic infrastructure.

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Session 8 : WIM Technology Assessment

Chair: Lily Poulikakos (EMPA, Switzerland)

WIM SENSOR PERFORMANCE AND STABILITY ACROSS TIME PERIODS AND VARIATIONS IN TEMPERATURE




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Abstract
This paper reports on the performance and stability of Weigh-In-Motion (WIM) sensors evaluated over temperature variations and time, with sites in South America and the United States operated by private operators and state DOTs. Understanding the accuracy and precision of WIM sites over temperature and time assists in evaluation of calibration intervals, and if they need to be adjusted to maintain performance consistent with local WIM standards.

The data collected from Oregon, USA and Argentina was collected from mainline WIM sites, with data for analysis constrained to 70km/h to 115 km/h. The sites were not recalibrated at any point during the trial. A meta-analysis of WIM front axle data showed no significant or systematic correlation of deviation from mean in WIM performance over time and temperature change.
Keywords: Weigh-In-Motion, WIM, High Speed WIM, HS-WIM, Strip Sensor, mainline WIM, data collection, direct enforcement strain gauge, ASTM 1318, COST 323, OIML R134

Résumé
Ce document présente les performances et la stabilité des capteurs Weigh-In-Motion (WIM) évaluées en fonction des variations de température et de la durée, avec des sites situés en Amérique du Sud et aux États-Unis exploités par des opérateurs privés et des DOT des Etats Unis. Comprendre l'exactitude et la précision des sites WIM en fonction de la température et du temps facilite l'évaluation des intervalles d'étalonnage, et si ceux-ci doivent être ajustés pour maintenir des performances conformes aux normes WIM locales.

Les données collectées en Oregon aux États-Unis et en Argentine ont été collectées à partir des principaux sites WIM, les données pour analyse étant limitées à 70 km / h à 115 km / h. Les sites n’ont été recalibrés à aucun moment. Une méta-analyse des données d'essieu avant WIM n'a montré aucune corrélation significative ou systématique de l'écart par rapport à la moyenne de la performance WIM en fonction du temps et de la temperature

Mots-clés: Poids très en mouvement, WIM, WIM haute vitesse, HS-WIM, capteur de bande, WIM principal, collecte de données, jauge de contrainte à application directe, ASTM 1318, COST 323, OIML R134

1. Introduction

The goals of monitoring and enforcing gross vehicle and axle weight limitations on roadways is crucial to protect road infrastructure and maintain operator (driver) safety. Countries and regions may differ in the standards and technology used to achieve these goals, with strain gauges commonly used in the load cells of static truck scales that are widely accepted as the most accurate means of weighing trucks for enforcement and commerce.

The development of Weigh-In-Motion (WIM) sensor technology and systems has led to the use of this method of weighing in mainline tolling (Electronic Toll Collection, or ETC,) data collection, screening for enforcement, pre-selection for weigh stations, and direct enforcement. With adoption in systems that include legal enforcement where local legislation allows, understanding the accuracy and stability over time and temperatures enables setting appropriate calibration intervals to ensure performance of the WIM system.

High speed WIM systems are now available that meet the requirements for weight based applications, expanding on the capabilities that static weighing systems provide. The analysis was done on strain-gauge based WIM systems which offer relatively low cost sensors compared to those with a similar form factor, short installation timelines of less than 1 day, and does not require a drainage system. Based on in-road Intercomp strip sensors, these sensors are connected to either the Intercomp WIMLogix CPU or other electronics.

Intercomp Company was founded in 1978 and has specialized in designing and manufacturing strain gauge-based 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. Dynamic (WIM) designs, including medium and high speed systems, have been refined for use in applications ranging from ports of entry, data collection, tolling (ETC) and enforcement.

2. Strain Gauge Strip Sensor

Although there are advantages and disadvantages to every method of measuring a load, there is a reason that precision electronic scales use strain gauge-based load cells. Though designed and calibrated for WIM use, strain gauge based equipment can be tested 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. Internal temperature compensation ensures that strain gauge sensors remain accurate over temperature extremes encountered outdoors and in pavement.

The in-road WIM sensors are based on high performance strain gauge technology and are available in lengths of 1.0, 1.5, 1.75 and 2 meters operating in pairs to cover the entire traffic lane. The systems typically consist of strip sensors placed in the roadway, cabinet mounted CPUs for A/D conversion, loop sensors, and a computer for transmission or data storage.

3. Background

It is the inherent stability of the strain gauge load sensing devices with temperature compensation done at the load cells, that lend itself to precision over variations of temperature and passing of time. Through the development and deployment of strip sensors throughout the world, Intercomp has received feedback from operators of the WIM sites regarding the stability of sensor data over time and temperature extremes.

A study by (Rygula, et al) of WIM sites operated by APM PRO sp.z.o.o, investigated sites that were using bending plate scales, strain gauge strip sensors, and piezo quartz sensors for in-road WIM sensors. The study was done to evaluate statistical tools to monitor long term stability of different WIM sites. Representative histograms from this study are shown in Figure 1 - bending plate, Figure 2 – strain gauge strip sensors, and Figure 3 – piezo quartz.

Table 1: Evaluation of WIM Sites from Poland

WIM station	Weight sensors	Class	Road type	Average daily traffic [veh. Per day]
Cierpice	Bending plate	B+(7)	Single carriageway with 2 lanes	11743
Strzelno	Strain Gauge Load Cell Sensors	B+(7)	Single carriageway with 2 lanes	10528
Głuchowo	Quartz sensors	B+(7)	Single carriageway with 2 lanes	8224

As part of the analyses, the dataset was limited to four basic periods of the year represented by the following intervals: August 2017, October 2017, November 2017, and January 2018

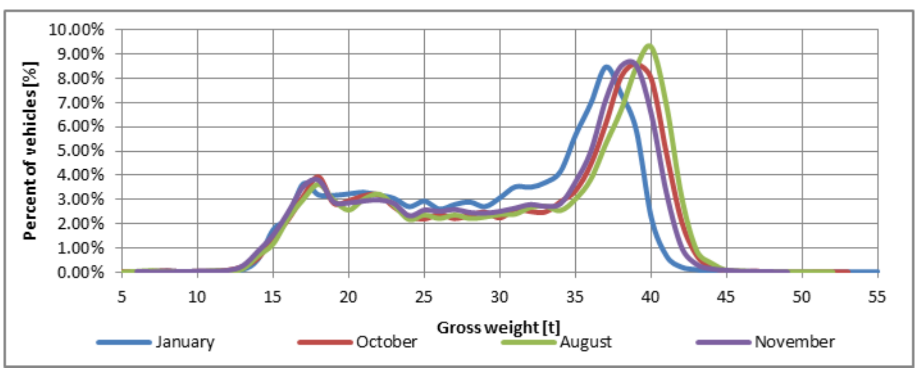

Figure 1 – BENDING PLATE GVW Histogram, Cierpice, Poland

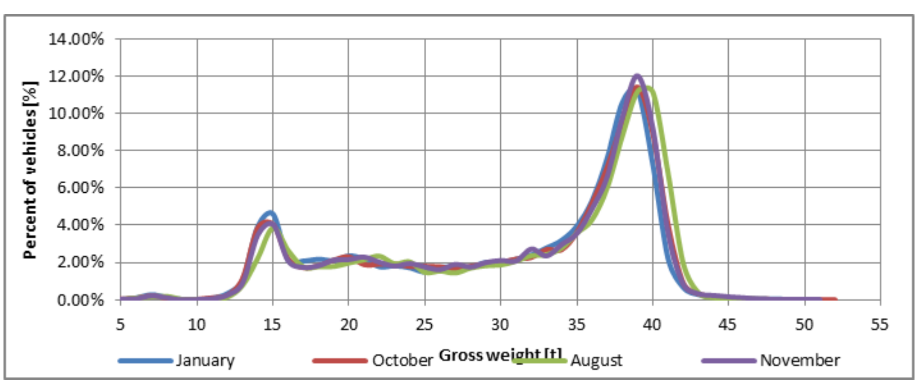

Figure 2 – STRAIN GAUGE GVW Histogram, Strzelno, Poland

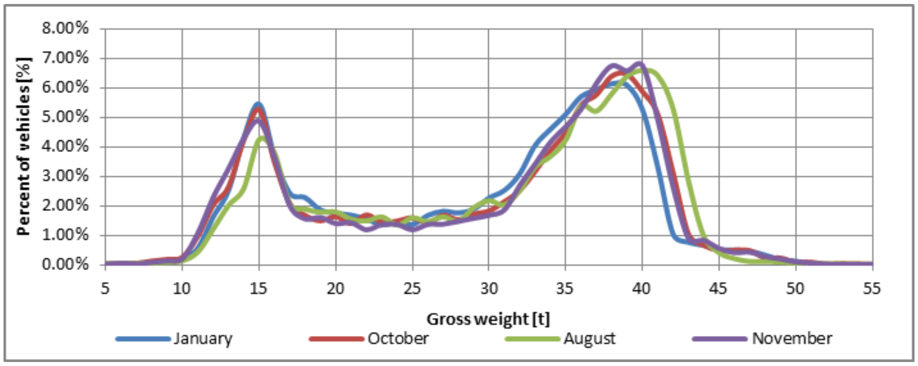

Figure 3 – PIEZO QUARTZ GVW Histogram, Głuchowo, Poland

Based on the internal testing, the information in the above study, and feedback from WIM operators, this paper intends to explore additional data and methodology to investigate WIM strain gauge sensor performance and stability.

4. Methods

The testing for this paper was completed at two different locations focusing on 5-axle vehicles. Though exact configurations vary by geography, multiple axle segmented trucks are the most common commercial vehicles used in transportation of commercial goods. The vehicles transited the Intercomp strip sensors at speeds that ranged from 45 mph (72 km/h) to 85 mph (137 km/h), but data for analysis was constrained to 70km/h to 115 km/h. The trucks passed over the strip sensors and their axle and gross vehicle weights were recorded.

The authors applied an analysis to the front axle vehicle data for both test sites, to assign a statistical value to vehicle data that was used to create histograms. With recognized consistency for front axle weights within 5-axle configurations and large amounts of vehicle traffic, it is suggested that any significant 'drift' of the mean values of large samples would largely be due to WIM site performance. Any effects of temperature would be consistently seen during summer or winter months, and drift over time from site calibration may also be observed.

The data is presented in this paper.

4.1 Evaluation Test Sites

Oregon Department of Transportation (ODOT) operates multiple WIM sites upstream of static scales for screening for enforcement purposes. Vehicles travelling on the mainline interstate were weighed on 4 sensors configured in two rows of strip sensors which are connected to ISINC® electronics manufactured by International Road Dynamics, Inc (IRD). Inter-row spacing for the dual threshold site is 4m. The output from the strip sensors undergoes A/D conversion in the IRD electronics, and the data is managed by ODOT.

The authors requested data from ODOT, and ODOT personnel independently selected the LaGrande, Oregon site as the primary data source for this paper due to the temperature variations experienced at the site throughout the year, and the elapsed time since calibration. These data were compiled from a mainline site which experiences up to 10,000,000 vehicles per year. Calibration was last done at the LaGrande WIM site in September of 2016. The data presented below is for 21 months beginning in January of 2017 through Sept 2018, or 2 years elapsed since the last calibration date.

Figure 4 – ODOT LaGrande, Oregon USA WIM site

American Traffic SA (ATSA) operates multiple WIM sites in highways and mainline locations for multiple WIM applications. Vehicles travelling on the highway were weighed on two strip sensors configured in two staggered rows with 4m spacing, which are connected to Intercomp WIMLogix electronics. The output from the strip sensors undergoes A/D conversion in the WIMLogix electronics, and the data is sent to a server operated by ATSA.

The authors requested data from ATSA, and ATSA personnel presented data from 14 sites available for analysis. The San Pedro site was selected for the relatively large amounts of 5-axle traffic experienced by the WIM site. Calibration of the San Pedro site was conducted in the 6 months prior to the data being gathered. The 2 sensor HS-WIM site have a 4m spacing, and were installed as shown in Figure 5. Additional sensors may be added to increase the accuracy of the system

Figure 5 – ATSA San Pedro, Argentina WIM Site

The HS-WIM system at ODOT used 4 sensors and the HS-WIM system in Argentina used 2 sensors.

4.2 Sample Test Vehicles

For the meta-analysis at both sites, 5-axle vehicles were selected. In the US, this will result in primarily Class 9, 5-axle tractor and semi-trailer configurations, with the potential for Class 7 and Class 11 vehicles. The site experienced 38,718 5-axle vehicles on average per month. Maximum allowable weight is 80,000 lb (36,300 kg) without special permits

In Argentina, all 5-axle vehicles were selected. There are multiple vehicle classifications with this number of axles, with maximum allowable GVWs ranging from 92,594 lb (42,000 kg) to 99,208 lb (45,000 kg.)

5. Results

The results from LaGrande, Oregon in Figure 6 below illustrate the front axle weights of 5-axle trucks sorted by month over 21 months of testing. Average monthly temperatures ranged from 21.8^{o}F (-5.7^{o}C) to 74.6^{o}F (23.7^{o}C.) . The graph indicates qualitative peak repeatability over a 21-month span.

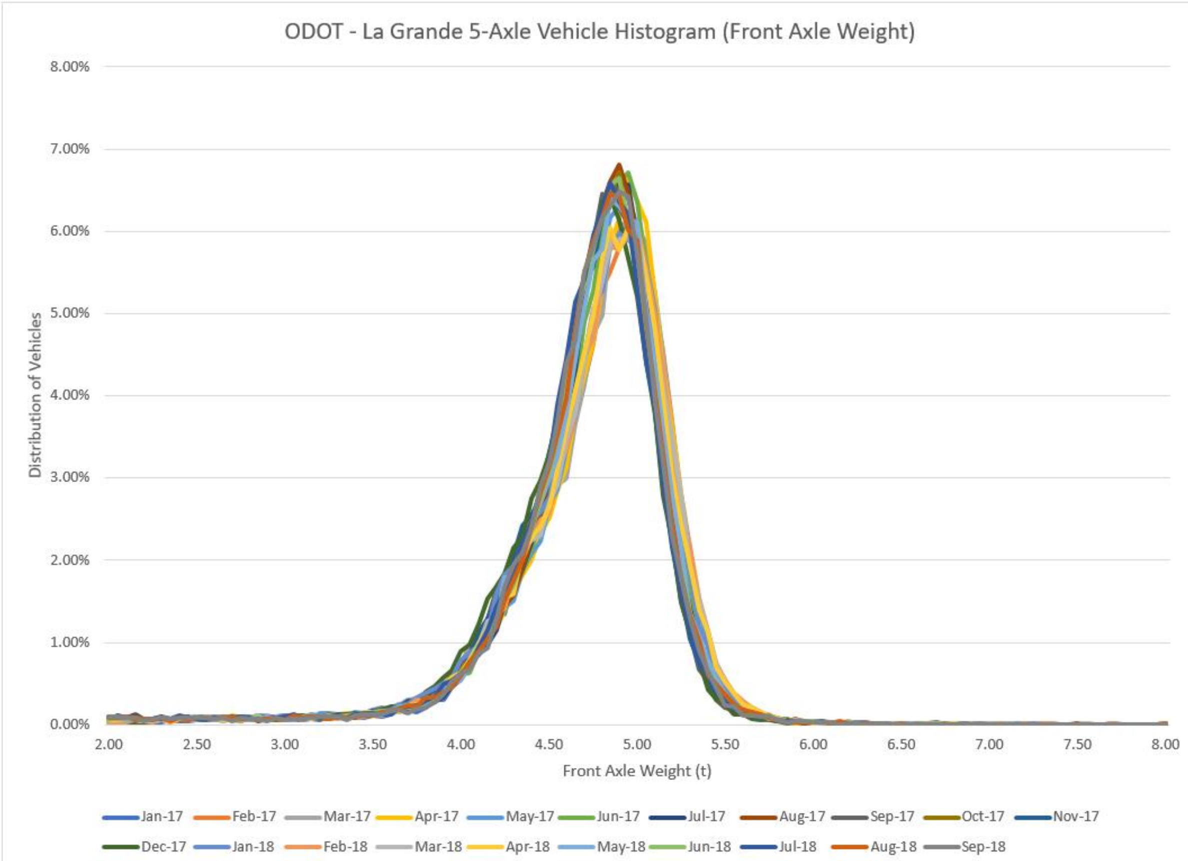

Figure 6 – ODOT LaGrande 5-axle Vehicles, Front Axle Weight by Month (n=813,070)

Table 1 displays 21 months of data from January 2017 through September 2018. Data was constrained to vehicle speeds ranging from 70km/h to 115 km/h. On average, 38,718 5-axle trucks crossed the WIM site per month. The deviation from the mean for front axle weights ranged from -0.9% to 0.9%.

Table 1 - ODOT LaGrande Front Axle Data (21 months)

Month	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17
Count (5-Axle)	28667	34620	44426	41916	41257	38763
Average (kg)	4779	4771	4769	4770	4747	4747
Deviation from Mean	0.8%	0.7%	0.6%	0.7%	0.2%	0.2%
Avg Temp (C)	-5.7	1.8	6.1	7.5	13.3	17.3

Month	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17
Count (5-Axle)	37276	37647	38624	42148	39631	29477
Average (kg)	4739	4731	4698	4708	4695	4695
Deviation from Mean	0.0%	-0.2%	-0.9%	-0.7%	-0.9%	-0.9%
Avg Temp (C)	23.7	22.2	16.5	8.5	5.1	-2.0

Month	Jan-18	Feb-18	Mar-18	Apr-18	May-18	Jun-18
Count (5-Axle)	38053	34728	47583	41935	43507	39987
Average (kg)	4737	4781	4768	4760	4741	4720
Deviation from Mean	0.0%	0.9%	0.6%	0.4%	0.0%	-0.4%
Avg Temp (C)	2.9	0.9	4.4	9.0	16.0	16.7

Month	Jul-18	Aug-18	Sep-18
Count (5-Axle)	39503	41840	31482
Average (kg)	4707	4732	4723
Deviation from Mean	-0.7%	-0.2%	-0.3%
Avg Temp (C)	22.9	22.4	15.9

The front axle error was plotted over time and temperature at the WIM site in Figure 7. Minimal relationship between temperature and front axle error was observed, with an R squared value of 0.1354 (13.5%.)

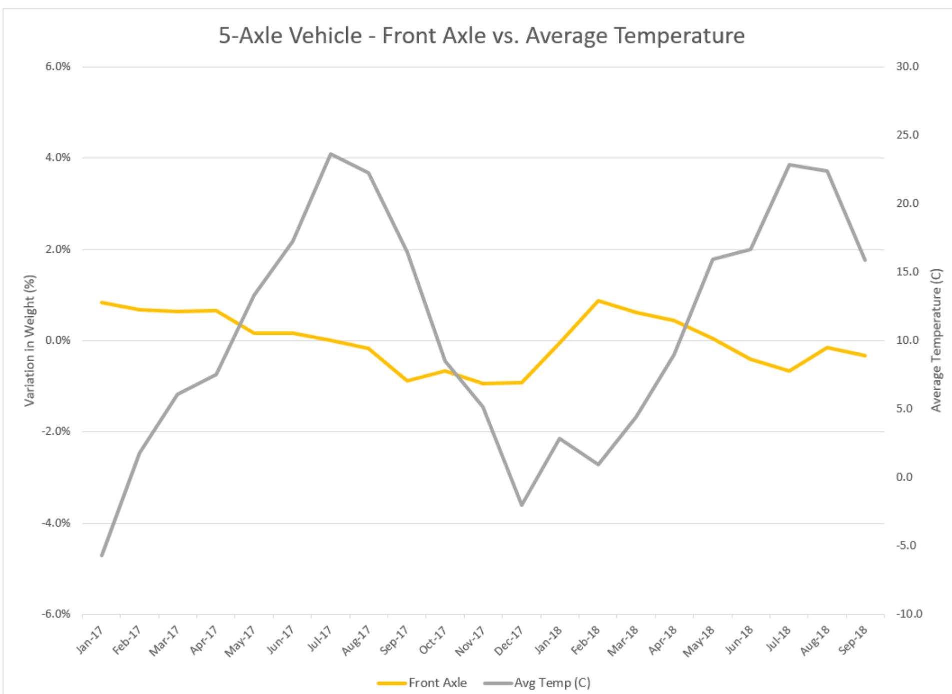

Figure 7 – ODOT LaGrande Front Axle Deviation from Mean Over Time and Temperature

A smaller dataset and timeframe were used at a site in San Pedro, Argentina as shown in Figure 8. This histogram illustrates the front axle weights sorted by month of 5-axle vehicles. On average, 7,185 5-axle trucks crossed the WIM site per month. Average monthly temperatures ranged from

51.9°F (11.1°C) to 71.8°F (22.1°C.) A minimal relationship, but larger than ODOT data, between temperature and front axle error was observed, with an R squared value of 0.3683 (36.8%.)

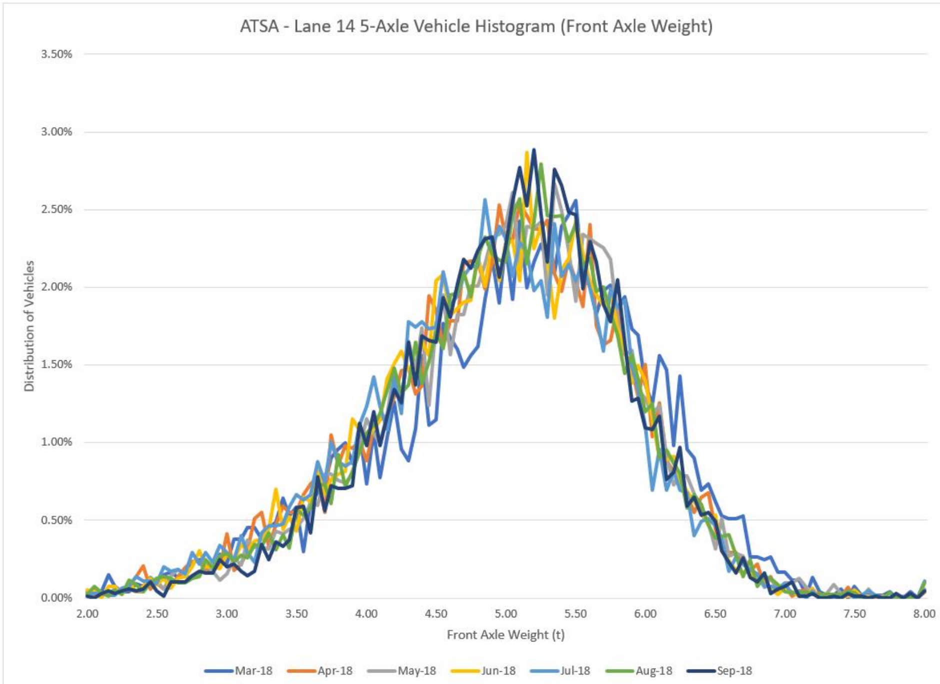

Figure 8 – ATSA San Pedro 5-axle Vehicles by Month (n=50,296)

Table 2 displays 7 months of data from March 2018 through September 2018. Deviation from the mean for front axle weight varied from -1.6% to 1.7%.

Table 2 – ATSA Front Axle, 5-Axle Vehicle Data (7 Months)

Month	Mar-18	Apr-18	May-18	Jun-18	Jul-18	Aug-18	Sep-18
Count (5-Axle)	5321	7261	7028	7901	6497	9352	6936
Average (kg)	5079	4963	5024	4955	4916	5003	5026
Deviation from Mean	1.7%	-0.6%	0.6%	-0.8%	-1.6%	0.2%	0.6%
Avg Temp (C)	22.1	21.6	16.7	11.1	11.1	12.0	16.8

6. Discussion

To investigate WIM sensor stability over temperature and time, a meta-analysis of front axle weights over time and temperature is applied and presented for the data sets above.

There are potential sources of variation that may negatively affect the analysis that would need to be accounted for, if present:

1. Inherent accuracy of WIM sensors (2 vs. 4 per lane, ATSA vs. ODOT in examples)
2. Seasonal trends in commercial vehicles – shipping agricultural products, for example
3. Multiple vehicle classes with same axle configurations, but different allowed weights

4. Regional compliance to weight limits
5. General vehicle and roadway conditions in geography

With the South American WIM site, only two sensors per lane were present, with five vehicle classes with two different maximum allowable weights. Sample size was smaller, decreasing the value of an analysis. This highlights the contrast to the Oregon site.

Where robust and consistent vehicle data exists (to remove potential variables), site performance may be able to be monitored via remote analysis tools to determine stability and for calibration interval requirements. The Oregon, US data meets most if not all criteria for this to be applied.

7. Conclusion

The data presented in this paper demonstrates the stability over time and temperature of the strain gauge based strip sensors. Using front axle weights, a minimal relationship between WIM site performance over temperature variations and time was observed.

Using the proposed front axle meta-analysis on the smaller ATSA dataset with fewer vehicles, broader vehicle weight ranges of vehicle classifications, a shorter period of time, and lesser temperature variation results in less conclusive trends.

Conducting the same analysis for the ODOT data, up to 24 months after calibration, without performance concerns from the end user, degradation of performance over time, and minimal to no relationship to changes in temperature during the timeframe investigated.

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STUDY OF THE DYNAMIC EFFECTS OF LOADS AND ACTIONS TO REDUCE THE UNCERTAINTIES



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Abstract

This paper presents the results of the study of the dynamic effect of the load and actions to reduce the uncertainties caused. For this, the review of the studies that consider the dynamic oscillation of loads in the accuracy of WIM systems will be presented. At first, the analysis of the experiments performed at the experimental site Brazil will be presented, comparing the results obtained from the instrumentation of the load vehicles with the data obtained with the WIM sensors. In a second part, the analysis of the results of the experiments performed on the IFSTTAR fatigue carousel in Nantes, France, will be compared. Finally, it will be discussed the need to correct the effect of vehicle dynamics and possible methods to decrease uncertainties and increase the accuracy of WIM systems.

Keywords: weigh-in-motion, WIM accuracy, vehicle dynamics, road profile, pavement and sensor interaction.

Résumé

Cet article présente les résultats de l'étude de l'effet dynamique de la charge et les actions visant à réduire les incertitudes causées. Pour cela, nous présentons la synthèse des études prenant en compte l'oscillation dynamique des charges dans la précision des systèmes WIM. Dans un premier temps, l'analyse des expériences effectuées sur le site expérimental du Brésil sera présentée, comparant les résultats obtenus de l'instrumentation des véhicules de charge aux données obtenues avec les capteurs WIM. Dans une seconde partie, l'analyse des résultats des expériences réalisées sur le carrousel de fatigue de l'IFSTTAR à Nantes, en France, sera comparée. Enfin, il sera discuté de la nécessité de corriger l'effet de la dynamique du véhicule et des méthodes possibles pour réduire les incertitudes et augmenter la précision des systèmes WIM.

Mots-clés: pesage en marche, précision WIM, véhicule dynamique, l'uni longitudinal, chaussée et capteurs WIM.

1. Introduction

The Araranguá test site in Santa Catarina is located at km 419 of route BR-101, south of Brazil. It is supported by the National Department of Terrestrial Infrastructure (DNIT), which is part of the Ministry of Transport since 2007. The experimental site consists of three locations with specific applications of WIM technologies. In the first site, called Integrated Station, studies are carried out with market available commercial systems and with WIM applications where a metrological certification is not necessary and that allow integration to other systems. Applications for these systems include classificatory counting of vehicles with weighing, pre-selection of vehicles for the inspection of excess loads and for applications in toll plazas. In the second location, called the traffic control station, studies are carried out with sensors and systems for the design of a technological model with application for Direct Surveillance. The third site is the weighing station, where studies are carried out to define the operational model of the Integrated Automated Enforcement Station (initials in Portuguese are PIAF), the current weighing model adopted on federal highways.

During the test period, soon after the installation of the WIM systems, tests were carried out with instrumented trucks. Four classes of heavy vehicles were chosen, representing 80% of the fleet's cargo vehicles. The classes of load vehicles used in the tests are: heavy truck with 2 axles, heavy truck with 3 axles, semi-trailer truck with 5 axles and semi-trailer truck with 6 axles. The vehicles were instrumented with strain-gages glued on the axles, left and right side, and accelerometers glued to the body. A data acquisition system collected data in real time. The collected signals were processed and crossed with information from a coupled GPS system; both devices working synchronously determined the position of the vehicle with respect to the track and with respect to the WIM system.

This paper presents the results of the study of the dynamic effect of the load and actions to reduce the uncertainties caused. For this, the review of the studies that consider the dynamic oscillation of loads in the accuracy of WIM systems will be presented. At first, the analysis of the experiments performed at the experimental site Brazil will be presented, comparing the results obtained from the instrumentation of the load vehicles with the data obtained with the WIM sensors. In a second part, the analysis of the results of the experiments performed on the IFSTTAR fatigue carousel in Nantes, France, will be compared. Finally, it will be discussed the need to correct the effect of vehicle dynamics and possible methods to decrease uncertainties and increase the accuracy of WIM systems.

2. Road profile and vehicle dynamics

Roadway pavement surfaces usually present longitudinal variations, due to imperfections during construction or to permanent deflection during its service life. Such defects on the road profile cause dynamic perturbations on passing vehicles, causing movements that affect the comfort and safety of passengers, depending on the excitation frequency. They are also the cause of the dynamic overload that accelerate pavement degradation (LCPC, 2009). The variations of the height z of the surface along a longitudinal curve x are defined as the longitudinal profile.

Approaching the WIM sensor, the forces transmitted to the pavement vary according to the dynamic acceleration in each instant t. The weighing sensors detect the stresses exerted on its surface on the instant of the load passage. The resulting vertical force $F(t)$ on the sensor is proportional to the equivalent static force $F_s = m \cdot g$ (mass under the effect of constant gravity acceleration) combined with the dynamic force in a given instant $F_d\ (t) = m \cdot a(t)$ (mass under the effect of the resulting dynamic acceleration at instant t). Hence,

$$F(t) = F_s + F_d\ (t) \tag{1}$$

Where: $F(t)$ is the vertical resulting force for each instant t; F_s is the equivalent static force, here considered unaltered; $F_d(t)$ is the dynamic force, which is a function of the roadway profile for instant t in time.

A schematic of the vehicle dynamics is presented in Figure 1. The force $F(t)$ travels at velocity V in the direction of the weighing sensor at a distance determined by Vt. The weighing sensor is at the center of the $[-l; l]$ interval, precisely at $t = 0$. The sensor measures with precision the force $F(0)$. The acceleration $a(t)$ acts on the vehicle mass over the proximity of the WIM sensor. The acceleration $a(0)$ acts at the moment when the load is over the sensor surface. The force action on the sensor corresponds to $F(0) = m \cdot g + m \cdot a(0)$. Negative values of acceleration represent a resulting force inferior to F_s.

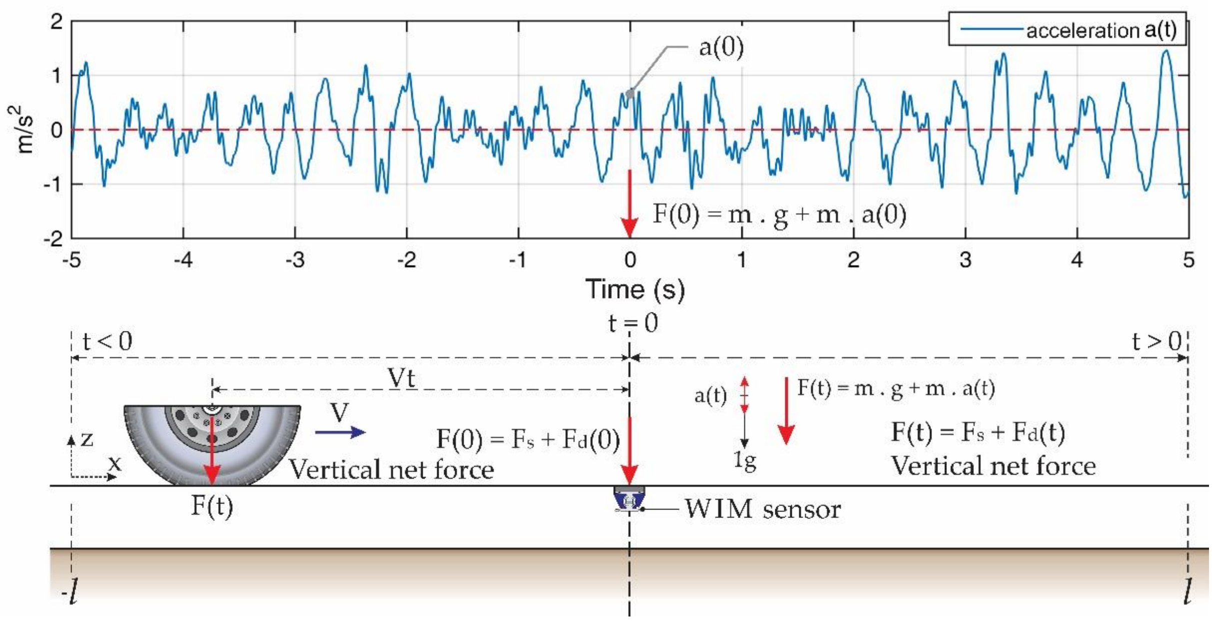

Figure 1 - Effect of the dynamic load over the WIM site, dynamic variation of the applied force and reading of the weighing sensor at instant $t = 0$

The correction of the dynamic effect of the load over the WIM sensor can be considered from the identification of the relation r between the resulting vertical force $F(0)$ and the value of the equivalent static force $F_s \approx \overline{F}$.

$$r = \frac{F(0)}{\overline{F}} \tag{2}$$

Where: r is the correction coefficient for the dynamic force measured at instant $t = 0$; $F(0)$ is the resulting vertical force at instant $t = 0$; $\overline{F}$ is the equivalent static force approximated by the average value of the force $F(t)$. The parameter r considers the fact that using the force's average value over sufficiently large periods reduces the effect of dynamic variation.

2.1 International roughness index - IRI

The International Roughness Index (IRI) adopts as input the defects of the longitudinal profile with wavelength L between 1 and 30 meters and attenuates the defects that are not in this interval. The displacement velocity of the Golden Car is fixated at 80 km/h, and the IRI is approximately sensitive to the frequency band between 0,7 Hz and 22 Hz. The index is calculated as the sum of the differences between the vertical position of the suspended and unsprung mass at the stretch comprehended in L, corrected by the velocity. It can be expressed as follows:

$$IRI = \frac{1}{L}\int_0^{L/V} |\dot{z}_s(t) - \dot{z}_u(t)| dt \tag{2}$$

Where V is the velocity, z_s is the vertical displacement of the suspended mass and z_u the vertical displacement of the unsprung mass. The calculated value for the IRI has the form of a decimal number between 0 (perfect irregularity) and the dimension of an inclination in m/m or m/km.

2.2 Note par Bande de Onde - NBO

In France, another measure used to characterize the irregularities of the transversal profile is the waveband notation (NBO). This method decomposes the profile in three spectral wavebands and analyzes each of them. The energy values (expressed in cm^3) are determined by the product of the sum of the squares of the amplitudes and the interval between two points (MENANT, 2014).

$$E = \Delta x \cdot \sum_{i=1}^{N} A_i^2 \tag{3}$$

Where Δx is the sampling step of the signal, N the number of points measured corresponding to the length of the segment and A_i the amplitude of the signal in cm. The calculation of the DSP consists of determining the power allocation of one signal due to a frequency scale. Here it can be defined as the square of the module of the Fourier transform of the signal $F\{x(t)\}$, divided by the frequency step df.

$$F\{x(t)\} = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}\, dt \tag{4}$$

$$DSP = \frac{|F\{x(t)\}|^2}{df} = |F\{x(t)\}| * np * dx \tag{5}$$

Where: $x(t)$ is the number of sampled points and dx the discrete displacement step. The section being analyzed must have length greater than 1000m, to ensure statistical accuracy. This application of the method with DSP only shows the defects with periodical characteristics (IDRRIM-CEREMA, 2014).

The average IRI value over the length of the experimental track is 2,2m/km to the left and 2,2 m/km to the right, with standard deviation of ±0,8 m/km (variation coefficient of 36%). The average value over a stretch of 200 m (between positions 280 and 480 m), centered at the region of the sensors, is of 2,2 m/km (left) and 2,0 m/km (right), with $\sigma = \pm$ 0,4 m/km (variation coefficient of 19%). The maximum values (average of left and right) at the experimental track and over the sensors are respectively 4,1 and 2,7 m/km, and the minimum values 1,1 and 1,7 m/km.

The site's classification, according to COST 323, with regard to the irregularities of the pavement over the region over the sensors, considering a characteristic value of 2,6 m/km (for a confidence interval of 98%, considering the values as a normal distribution), classifies the WIM site as Class II (good). Considering the values obtained by the NBO method, the experimental site was rated as Class III (acceptable), considering all the wave lengths.

3. Vehicle dynamics models

Studies as those of Menant (2014) and Cebon (1991; 1993), amongst others, simulate, using mathematical models, the dynamic forces of the vehicles for analysis of user comfort and/or the amplitudes of the dynamic forces transmitted to the pavement. In both studies, a numerical simulation allowed the determination of the mechanical behavior of the vehicles as a response to the effect generated by the longitudinal profile of the pavements.

The dynamic behavior of a vehicle can be mathematically represented with elements that represent physical properties, as in Figure 2. Elements such as the tire and the suspension are symbolized by a damped spring with constant stiffness. Two simplified models can be used for analysis of the dynamic behavior (CEBON, 1991; 1993; MENANT, 2014).

- The first is a simple axle with two degrees of freedom, known as 'quarter-car'.
- The second, two axles (anterior and posterior, in tandem) with three degrees of freedom, known as a longitudinal 'half-car' (by some authors known as 'walking-beam tandem').

The 'quarter-car' model, shown in Figure 2, has two degrees of freedom at the vertical displacements z_s and z_u. The elements that compose it are (CEBON, 1993): an unsprung mass m_u, that represents the mass of the tire, wheel, bearing and suspension arm, a suspended mass m_s, that represents the mass of the chassis supported by the wheel in question, a spring with constant stiffness k_t, placed between the unsprung mass and the surface of the pavement, that represents the tire (damping c_t in the tire can be considered negligible in relation to the spring stiffness), the parallel association of a spring with constant stiffness k_s and a damping coefficient c_s.

The 'walking-beam tandem' model (also known as 'half-car' model), is also represented in Figure 2, and consists of a suspended mass m_s, which is restricted to the vertical displacement z_s. A rigid beam connects the two axles, and is connected to the suspension spring by a connecting pin in its center. It allows a soft damped rotation vibration (pitch of the tandem axle) of the set beam/axle with frequency between 8 and 14 Hz, unless hydraulic dampers are placed between the axles and the vehicle frame. The beam/axle set has a mass of m_u and a pitching moment of inertia I_u. It moves with a vertical displacement z_u and pitch rotation θ_u. The input longitudinal displacement profile of the system for both wheels are z_{r1} and z_{r2}. This model represents the minority of suspensions that generate great dynamic variation of the tire/pavement contact forces due to the pitching movement of the unsprung mass, as well as the low frequency movement of the suspended mass (CEBON, 1991; CEBON, 1993).

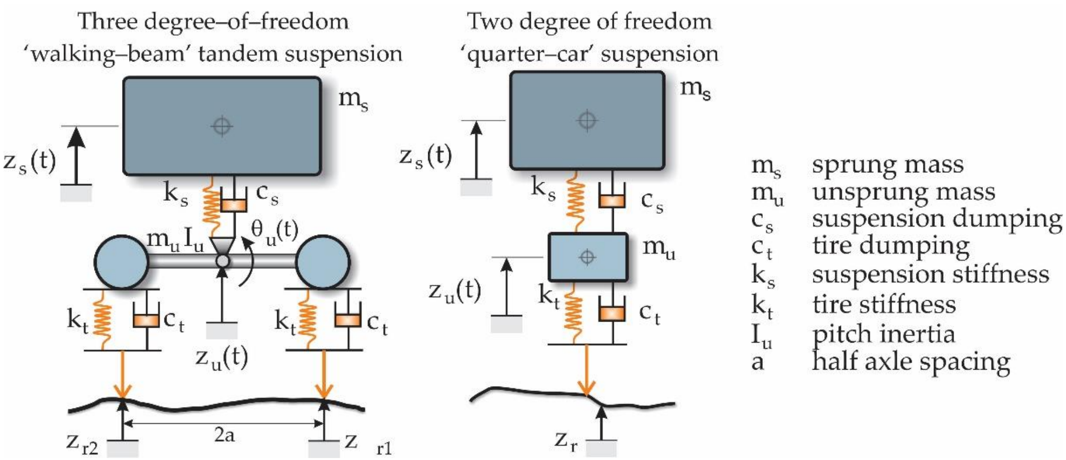

Figure 2 – Vehicle rigid body model

4. Instrumented vehicle test

The test conditions are: four trucks, near-average speed of traffic in the 60 km / h section, three empty loading conditions (tare), ½ load and full load (maximum limit for Total Gross Weight - PBT), number of the expected errors of dynamic force measurement.

The tests with instrumented trucks allow to access the different aspects of the dynamic behavior of the vehicles of load that travel by the highway. Determine the natural frequencies found in the body suspension assembly of the most representative vehicles of the fleet. For the WIM systems, one of the most important factors to consider is the natural frequency of the suspension and body assembly. The instrumentation procedure uses strain gauges attached to the bars of the axes (left and right side) that measure the strain and which are transformed (calibrated) into vertical force (the calibration of the system is performed with the vehicle stationary). Tri-axial accelerometers are glued to the body and measure the acceleration of the unsprung mass, in addition to data acquisition systems that collect and store the signals from these sensors.

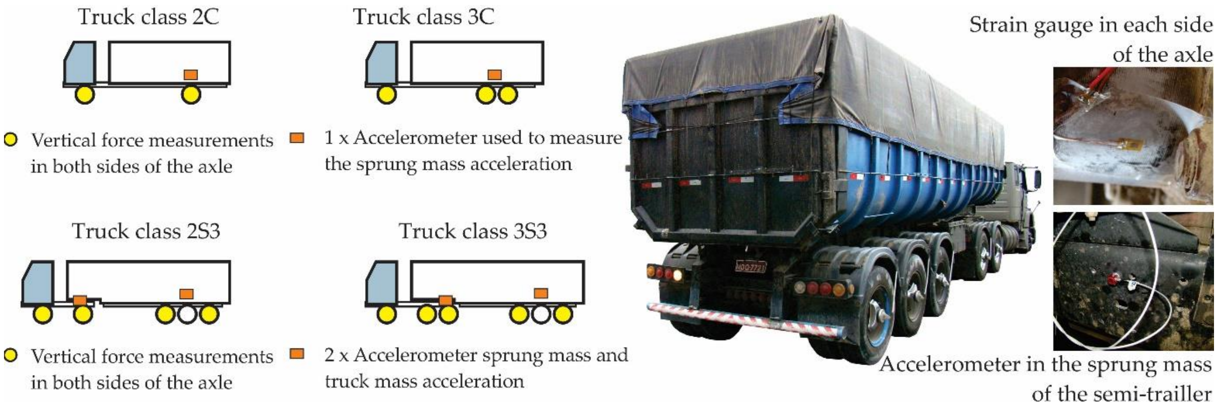

Figure 3 – Instrumented vehicle to measure sprung and unsprung mass accelerations

The recorded data include the forces by axle of the 3S3 class vehicle, loaded with Total Gross Weight (PBT), during a passage at velocity of 44 km/h (Figure 4). This vehicle is composed by a simple axle and a double tandem with drive axle (tractor) and a triple tandem (trailer).

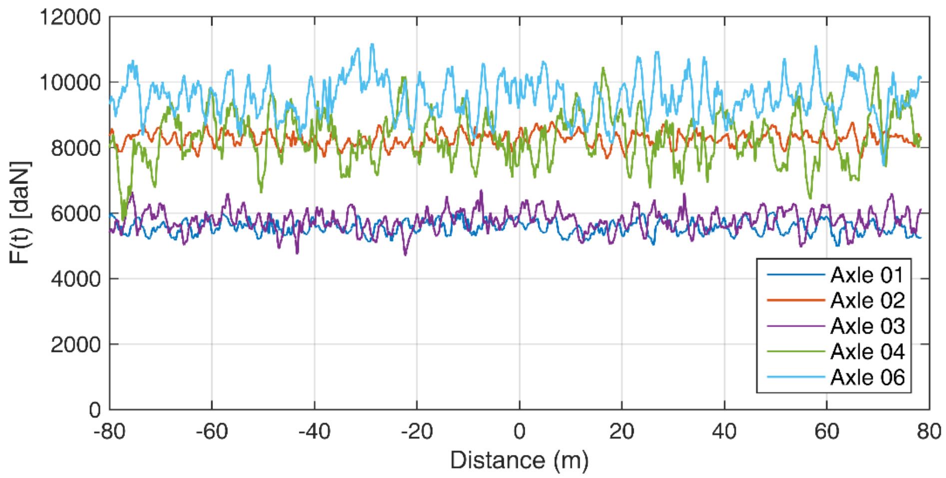

Figure 4 – Axle load forces F(t) of the Vehicle 3S3 travelling at speed of 44 km/h

Figure 5 shows the spectral power density (DSP) of the dynamic force of the 3S3 vehicle. The blue line represents the response for the E1 axle, in red the E2 axle, in yellow the E3 axle, in purple the E4 axle, and in green the E6 axle. The found characteristic frequency is 2,20 Hz for axles E1, E2 and E3 and 1,90 Hz for the remaining E4 and E5 axles. The frequencies found in (2) and (3), representing the effect caused by the wheel bearing over the pavement and the effect of the unsprung mass are, respectively, 7,92 Hz and 11,90 Hz.

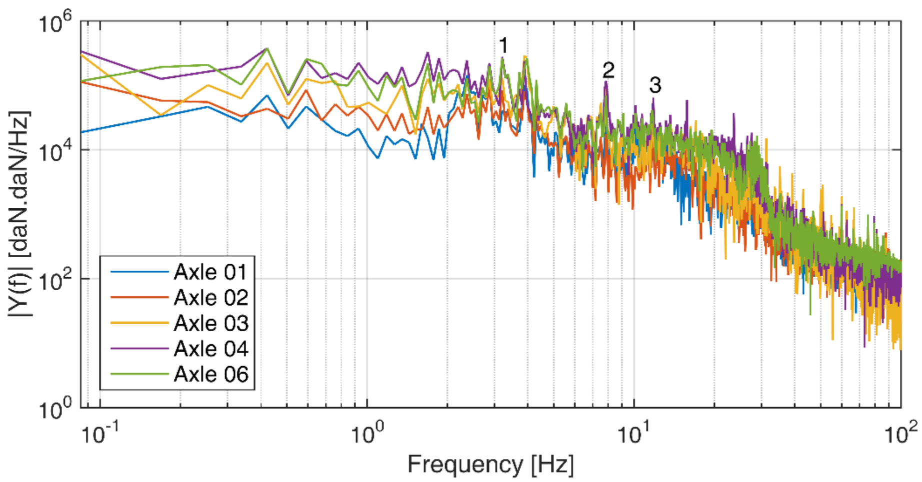

Figure 5 – Densidade espectral de potência (DSP) dos eixos dianteiro e traseiro (média de ambos os lados) do veículo 3S3

The characteristic frequency, to be considered for determining the spacing between the sensors in order to minimize load dispersion errors due to dynamic variations of the axles, for the WIM site, is 2,56 Hz.

5. WIM measurements

Figure 6 shows a superposition of W_d values over 10 passagens of the first axle (E1) of the truck 3C over the 16 WIM sensors, at a speed of 50 km/h. The abscissa axis represent the longitudinal distance over the WIM site, and the ordinate axis represent the weigh measured by each quartz sensor over the experimental track. In blue, the measurement of the strain gauges glued to the same axle, transformed into forces $F(t)$ in kgf. The superposition of the curves show similarities of the recorded dynamic behavior between the vehicle passing over the WIM sensors and the behavior registered by the instrumented vehicle, even if the measurements don't correspond to the same passing moment. The value of the reference static weight is W_s (E1 = 6522 kg).

Table 1 – Natural frequencies (Hz) for the axis of the characteristic vehicles of the experimental track

Vehicle fully loaded	Truck 2C	Truck 3C	Truck 2S3	Truck 3S3	Mean
Min	2,39	2,27	2,76	1,90	2,33
Max	2,90	2,77	3,22	2,30	2,80
Mean	2,64	2,48	3,02	2,11	2,56
-	-	-	-	-	2,56

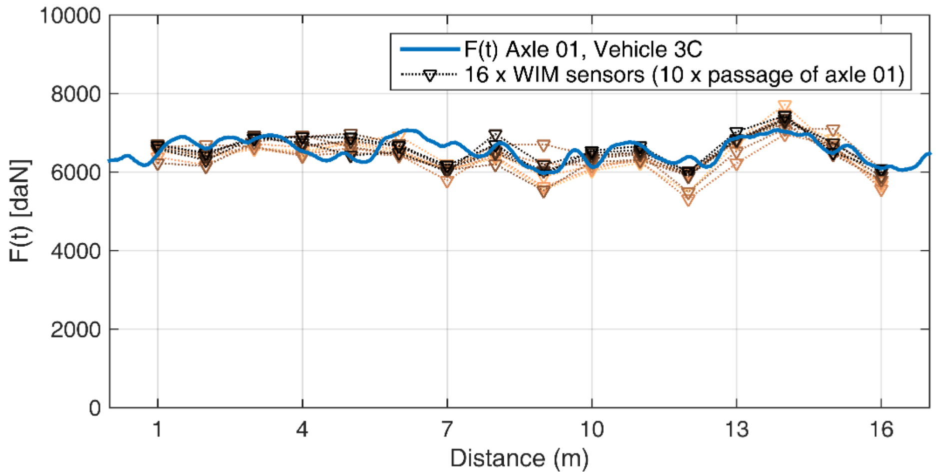

Figure 6 – Superposition between $F(t)$ of axle E1, from truck 3C, and W_d form WIM sensors

Let's consider that exist a way of measure the force F(t) of the axles do any truck passing over the WIM site. To correct the WIM measurement, is necessarily know the minimum length l needed to satisfy the least a certain error between the mean force $\overline{F}$ and the static weight W_s.

The minimum length l, in meters, needed to satisfy the error less than 3%, considering all trucks from the test site of Ararangua, is larger than 100 m, $l \geq 105$ m for an $error < 2\%$, and $l \geq 145$ m for an $error < 1\%$ (Figura 7).

Using the longitudinal profile from the pavement of the circular test track at IFSTTAR in Nantes and the Prosper-Callas numeric vehicle model simulation, for 5 axle truck traveling at speed of 32, 50 and 72 km/h. The minimum length l, in meters, needed to satisfy the error less than 3% is larger than 40 m, $l \geq 87$ m for an $error < 2\%$, and $l \geq 215$ m for an $error < 1\%$ (Figura 8).

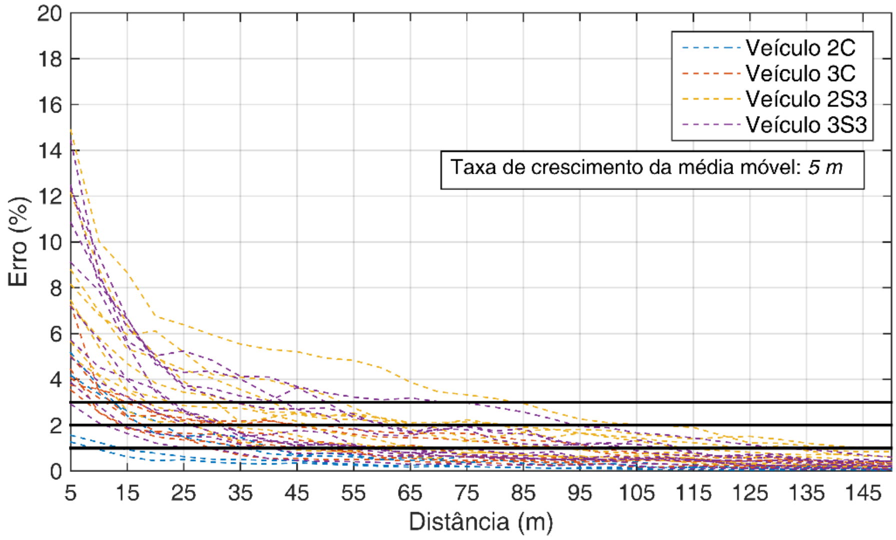

Figure 7 – The error and the minimum length l, in steps of 5 m, with the trucks classes 2C, 3C, 2S3 and 3S3

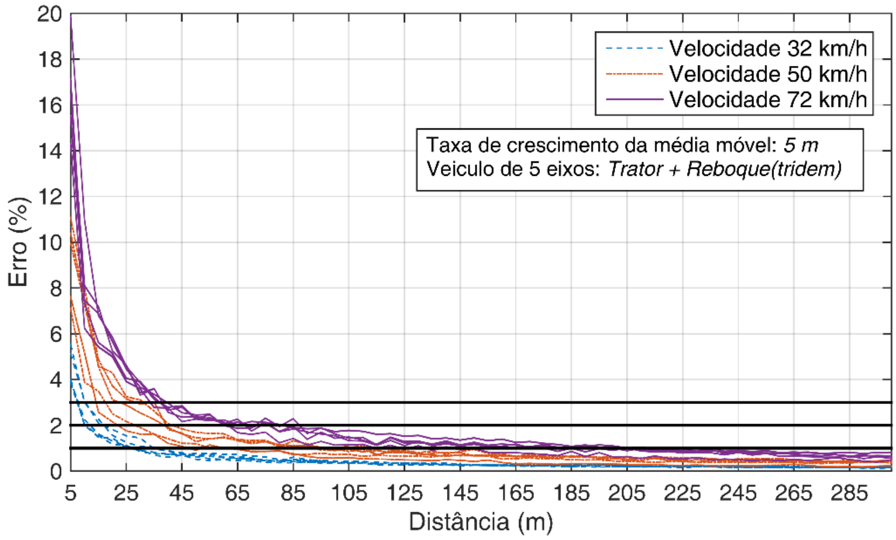

Figure 8 – The error and the minimum length l, in steps of 5 m, with the 5 axle form Prosper-Callas

6. Conclusions

The road profile of the roads and highways affect the vehicles dynamic, hence, the axle forces transmitted to the pavement varies accordingly. Those variations generate uncertainties for the high-speed WIM measurements, since calibration don't consider the vehicle dynamic. These uncertainties are the main reason why WIM systems are not able to measure with more accuracy. The instrumentation of all road vehicles is practically impossible. However, another method must be observed.

If we propose measure F(t) along the WIM site $[-l, l]$, even if those measurement are far less accurate than the WIM measurement. The approach presented here could be used to correct the

WIM measurements, obtained with an accurate WIM sensor, to reduce the uncertainties due to vehicle dynamics. Longer the WIM site, better the reduction the WIM uncertainties.

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BENDING PLATE WIM SYSTEM ANALISIS CONSIDERING THE DYNAMICS OF THE LOAD PLATFORM

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Abstract

This paper presents a numerical study on the behavior of weigh in motion systems based on bending plate WIM system. Some important parameters that may role this behavior are modeled: random road roughness, vehicle vertical dynamics, vehicle speed, load platform step's height to the road and dynamics of load platform. Two types of vehicles are evaluated numerically travelling at different speeds and being weighted. Ground reaction force and acceleration time history on several Degree of Freedom (DoF) are used to estimate the error of the measured weight for the rigid platform model. For the flexible platform model, the reaction forces serve as inputs into the Euler-Bernoulli finite element model with consideration of the contact area of the tire by train of loads. Conclusions concerning the importance of platform dynamics are obtained.

Keywords: Bending Plate, Weigh-in-motion, WIM, Dynamics, Road roughness profile, Finite element model.

Résumé

Ce travail présente une étude numérique sur le comportement de systèmes de pesage en marche basée sur le système WIM de bascule à jauges de contraintes. Certains paramètres importants pouvant représenter ce comportement sont: la rugosité aléatoire de la route, la dynamique verticale du véhicule, la vitesse du véhicule, la hauteur de la charge de la plate-forme sur la route et la dynamique de la plate-forme de chargement. Deux types de véhicules sont testés numériquement en se déplaçant à des vitesses différentes et en étant pesés. La force de réaction du sol et l'historique des temps d'accélération à divers degrés de liberté sont utilisés pour estimer l'erreur du poids mesuré pour le modèle à plate-forme rigide. Pour le modèle de plate-forme flexible, les forces de réaction servent d'intrants au modèle d'éléments finis d'Euler-Bernoulli en tenant compte de la zone de contact du pneu par train de marchandises. Des conclusions sur l'importance de la dynamique de la plate-forme sont obtenues.

Mots clés: Barreau de pesage, Pesage en mache, *WIM*, Dynamique, Profil de rugosité de piste, Modèle éléments finis.

1 Introduction

With the purpose of being able to evaluate the weighing in vehicle movement and to be able to model the main phenomena that occur, this work proposes a numerical study and modeling of these phenomena. Thus, the main objective is to analyze and model the bending plate weighing system of platforms (this technology is based on the measurement of deflection) commonly used in Brazil to verify the individual influence factors: the road roughness, vehicle type load platform step's height to the road and dynamics of load platform in the accuracy of the system One 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.

The finite element method is a computational tool developed around the 1950s and is widely used in various fields of engineering with analysis applications not only mechanical, civil structures, but also analysis of fluids, gases, etc. Currently there are several commercial software available to the engineer so you can use this tool in a more practical way. The importance of the method comes from the possibility of analyzing structures of more diverse forms and geometries, which in an approach by analytical solution would be possible in only some specific and well-defined cases, which is not common in practice This method starts from the approximation of the differential equations corresponding to a domain, in smaller problems corresponding to subdomains of the general problem. This is possible from the discretization by field of variables in elements (regions) and the hypotheses of continuity and form of variation of this field within the elements (form functions). Specifically, in the case of solids mechanics problems, in general, the displacement field is the field used to be approximated by interpolation functions called shape functions. These functions aim to satisfy the conditions of differentiability and continuity required by the equilibrium differential equations of the analysis in question. From a variational formulation assembled as a function of the potential energy, it is possible to arrive at the respective stiffness matrices of the structural problem in simple cases, and that for more complex cases can be obtained by the numerical integration. The formulation and deduction of the equations for the most diverse types of elements are found in a vast literature such as Bathe (2014), Ferreira (2009) and Reddy (2006) and that will not be the focus of this work.

For bridge weighing, the finite element modeling found in the literature ranges from finite elements of beams to three-dimensional elements that describe the geometry of the bridge. In the case of bending plates specifically, the modeling also varies from simple finite elements of beams to more complex models in plates or shells that better describe the geometry of the load cell type. The weighing platform in this work is modeled as a simply supported Euler-Bernoulli beam, a configuration similar to that found on the field platform where the platform is supported in the cradle of the track at the weighing site. This type of finite element has shape functions of the linear type for the displacement field and is suitable for modeling of beams that are thinned since the Euler model does not consider deformation by cutting. The weighing platform has a thickness that is much smaller than the other two dimensions: width and length.

2 Description of the numerical model

2.1 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 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 (1).

$$x(t) = \sum_{i=1}^{N} A_i Sin(\omega_i t + \phi_i) \tag{1}$$

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 (2):

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

The amplitude for each component of the function A_i (shift) is defined as, Equation (3):

$$A_i^2 = \sum_{i=1}^{N} G(n_i)\Delta n_i \tag{3}$$

Thus, the road profile is obtained by Equation (4):

$$x(t) = \sum_{i=1}^{N} \sqrt{G(n_i)\Delta n_i} Sin(\omega_i t + \phi_i) \tag{4}$$

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 velocity *v*.

2.2 Modelling the step between load platform and road surface

The link between the platform and the track is modeled as a kind bounce of type 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 to make sure the discretization in space is enough to represent the roughness of the road profile. More details can be found in (Gaspareto and Gomes, 2016).

2.3 Simulated and Tested Vehicles

There are two types of full vehicles being numerically tested: The type (a) vehicle presents a total mass of 2550 kg. It is assumed a wheelbase *Wb* of 2.312 m. It has 8 DoF (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. Details related to the equation of motion, further parameters and their values can be found in (Dhremer, 2012). The type (b) vehicle represents and actual passenger bus model IK301 with total mass of 18871 kg, wheelbase of 5.650m and width 2m. It has 10 DoF (with two suspensions bars, driver and passenger seats) that are suitable for bus/medium trucks. More details related to the bus model, equation of motion and values for the parameters can be found in (Sekulic´ *et al*, 2013).

2.4 Model of Load Platform

Two models are tested for the modeling of the phenomenon investigated here: (a) a first model that considers the weighing platform completely rigid, that is, without considering its deformation nor dynamic associated to the platform or interaction with the vehicle (Rigid Platform Model, RPM); (b) a second model where the platform dynamics was considered considering some vibration modes with the associated damping, in the reading of the measured forces (FPM). For the RPM model the vehicle reaction forces are used with the soil in the stretches of the platform using the vehicle, step and track modeling. For the FPM, these forces serve as input to the finite element model of Euler-Bernoulli beam considering the contact area of the tire. The full details of the model can be found in (Gaspareto, 2017)

2.4.1 Simple beam subjected to a moving Load

Yang *et al.* (2004) presents the analytical solution for the case of a simply supported beam subjected to a moving load modeled by a concentrated load force *p* and velocity *v*. The following hypotheses are adopted in this study: (a) the bar is homogeneous and of constant cross section, where Euler Bernoulli-Euler's hypothesis is satisfied that the flat sections remain flat after the deformation occurs; (b) only a single moving force is allowed to traverse the beam at a time; (c) initially only the applied force is considered, whereas the inertia effect of that which causes the force is neglected, assumed to be small in comparison with that of the beam; (d) the load moves at a constant velocity v, (e) the damping of the beam is of the Rayleigh type, (f) the beam is initially at rest before the load moves and (g) no consideration is given, initially, on the surface roughness of the beam.

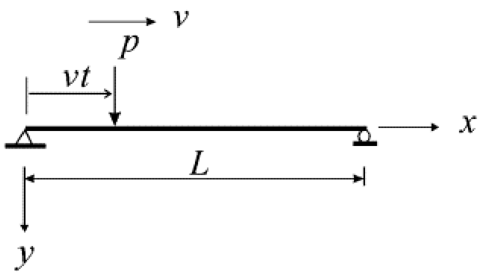

Figure 1- Simply supported beam traversed by a concentrated load *p* with velocity *v*.

As shown in Figure 1, a single beam is subjected to a load of magnitude *p* advancing at a velocity *v*. Here, *u (x, t)* denotes the deflection of the beam along the *y* axis at the position *x* and time *t*, *L* is the beam length, m is mass per unit length, c_e is the external damping coefficient, c_i the internal damping coefficient, *E* the modulus of elasticity and I the moment of inertia of the beam. Based on the above mentioned assumptions, the equation of motion of the beam can be written as (Equation 5):

$$m\ddot{u} + c_e\dot{u} + c_i I\dot{u}'''' + EIu'''' = p\delta(x - vt) \tag{5}$$

where the lines mean derivatives with respect to the space x and the points mean derivatives with respect to time, t is the time and δ means the Dirac delta function. For a beam with contour conditions simply supported, it is worth (Equation 6):

$$u(0,t) = 0, \qquad u(\mathrm{L},t) = 0, \quad EIu''(0,t) = 0, \quad EIu''(\mathrm{L},t) = 0 \tag{6}$$

And for the initial conditions of displacement and initial velocities at any point, null, assuming the beam at rest upon arrival of the moving load (Equation 7):

$$u(x,0) = 0, \dot{u}(x,0) = 0 \tag{7}$$

The dynamics of the platform can be modeled according to the presented equation, however the modeling becomes very complex analytically for cases of any platform geometries. Moreover the whole development is for punctual loads traversing the beam. For simplification in the resolution of the equation for the different regions of the weighing platform we use finite element modeling and integration using numerical methods such as the implicit Newmark method. This makes the treatment of the problem more generic and easier to implement as simulation of tire pressure, different cross sections along the length, coupling with vehicle dynamics, etc.

2.4.2 Tire contact area considerations

Each tire is simulated as a train of loads with length *(L_c)* relative to its contact length with the ground considered constant as a function of the tire radius (40% of the tire radius), values consistent with Castro (2013). The tire force (F_{pneu}) is divided by the total number of discrete loads of the freight train (N) used. In this work is used a discretization of the contact area of the tire with 100 parts and that proved adequate to represent this contact. Therefore, the weight of the tire is transmitted to the platform only if its current position on the axis of movement of the vehicle is within the platform, i.e. each element of train of loads (p_i) having a position greater than zero relative to the start of the platform and less than the length of platform L will be considered. For the rear tire the same criterion was used by discounting the distance between the axis of the current position x of the tire (see Figure 2).

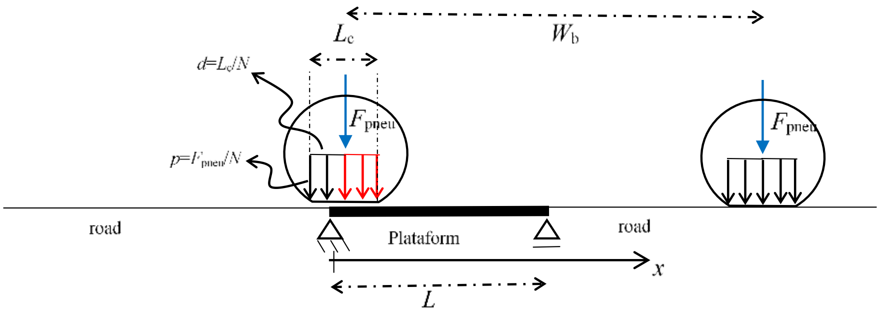

Figure 2- Representation of the tire contact area by equivalent train of loads

2.5 Dynamic Analysis

The vehicle dynamics including loading from the road roughness, load platform step and platform dynamics are modelled as usual as input forces and the equilibrium equation of motion in the discretized form takes the form, Equation (8):

$$[\mathrm{M}]\ddot{\mathbf{x}}(t)+[\mathrm{C}]\dot{\mathbf{x}}(t)+[\mathrm{K}]\mathbf{x}(t)=\mathbf{F}(t) \tag{8}$$

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. The choose time interval is based on road roughness accuracy representations and this results in time intervals several orders of magnitude lower than usual ($\Delta t=10^{-6}$ s) values assuring good precision to the resulted values.

3 Simulations

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 for the two models of platform (RPM and FPM). For a defined combination of parameters, the tests consisted on 100 simulations representing the actual variability of the weighting system and to evaluate the system accuracy. Random generation of road roughness and parameters allowed the variability between simulations. 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. 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 (Equation 9):

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

where Wd_i and Ws_i are the in-motion measured value and the static (reference) value”

3.1 Vehicle speed influence

This test presents the results of weight errors in case of vehicle speed variations for the models RPM and FPM. It was assumed five different vehicle speeds from 10 km/h to 80 km/h. The road class and step height were fixed. Tables 1 and 2 show the weight errors for vehicles type (a) and (b), respectively.

Table 1- GVW and weight per axle errors for vehicle speed variation and vehicle type (a)

Rigid Platform Model - 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%
Flexible Platform Model - 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	0,36%	2,08%	6,85%	2,06%	0,36%	2,12%	6,95%	2,10%
20 Km/h	1,21%	2,77%	7,15%	2,50%	1,19%	2,77%	7,19%	2,51%
40 Km/h	3,28%	7,84%	17,82%	7,15%	3,33%	7,94%	18,01%	7,24%
60 Km/h	3,73%	10,87%	28,13%	10,26%	3,82%	11,10%	27,52%	10,48%
80 Km/h	5,67%	12,00%	27,37%	10,63%	5,63%	10,67%	28,27%	10,67%

One can notice that both vehicle types (a) and (b) presented for this speed spam a good linear fit for the GVW error × vehicle speed. 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 for two models of platform. It can be noted that both FPM vehicle types (a) and (b) presented for this speed range a good linear fit for the RMS error at PBT × vehicle speed. The relationship between the standard deviation and the vehicle speed as the mean axle weight error and the corresponding standard deviation presented a similar linear behavior. For vehicle type (a), it was observed that the errors were close to the RPM value. For the vehicle type (b), the errors presented by the FPM were slightly smaller than the RPM, showing the importance of this modeling.

Table 2- GVW and weight per axle errors for vehicle speed variation and vehicle type (b)

Rigid Platform Model - 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%
Flexible Platform Model - 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	0,01%	0,40%	1,22%	0,40%	0,01%	0,41%	1,22%	0,41%
20 Km/h	0,50%	1,02%	3,14%	0,89%	0,55%	1,15%	3,17%	1,02%
40 Km/h	1,08%	3,97%	11,23%	3,97%	1,19%	4,07%	11,44%	3,91%
60 Km/h	2,75%	8,14%	21,69%	7,70%	2,81%	8,17%	22,23%	7,71%
80 Km/h	4,32%	10,53%	25,73%	9,65%	4,22%	10,35%	24,51%	9,50%

3.2 Step height influence

In this test, the step height was varied from -8 mm to +8 mm for constant vehicle speed and road class for the models RPM and FPM. The two vehicle types were tested. Tables 3 and 4 shows the numerical values obtained in this test for vehicles types (a) and (b), respectively.

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

Rigid Platform Model - 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%
Flexible Platform Model - 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	-11,28%	13,18%	-25,84%	6,86%	-11,48%	13,41%	-25,96%	6,97%
-4mm	-5,34%	8,08%	-22,71%	6,10%	-5,48%	8,25%	-23,24%	6,20%
-2mm	-3,43%	7,38%	-18,32%	6,57%	-3,48%	7,63%	-19,05%	6,83%
2mm	3,28%	7,84%	17,82%	7,15%	3,33%	7,94%	18,01%	7,24%
4mm	5,31%	8,57%	24,29%	6,76%	5,45%	8,77%	24,80%	6,91%
8mm	12,15%	13,84%	26,13%	6,66%	12,29%	14,05%	26,46%	6,84%

It was verified that for both vehicles types (a) and (b) the step height is an important factor. For the GVW mean error, 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. For vehicle type (a), it was observed that the errors were somewhat larger than in RPM. For vehicle (b), the errors presented by FPM were smaller than RPM.

Table 4- GVW and weight per axle errors for step height variation for vehicle type (b)

Rigid Platform Model - 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%
Flexible Platform Model - 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	-7,02%	7,75%	-14,62%	3,31%	-7,22%	8,05%	-15,08%	3,58%
-4mm	-3,21%	5,22%	-12,55%	4,14%	-3,23%	5,27%	-12,61%	4,18%
-2mm	-1,75%	4,21%	-12,56%	3,84%	-1,84%	4,33%	-12,46%	3,94%
2mm	1,08%	3,97%	11,23%	3,97%	1,19%	4,07%	11,44%	3,91%
4mm	3,93%	5,52%	13,66%	3,90%	3,93%	5,55%	14,28%	3,94%
8mm	7,10%	8,04%	14,29%	3,79%	7,29%	8,24%	14,39%	3,86%

3.3 Road roughness influence

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 5 and 6 shows the numerical results for the simulation for vehicle type (a) and for vehicle type (b), respectively.

Table 5- GVW and weight per axle errors for road class variation and vehicle type (a)

Rigid Platform Model - 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%
Flexible Platform Model - 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)	3,10%	4,30%	9,83%	2,99%	3,17%	4,39%	9,86%	3,06%
B (C_n=2)	3,28%	7,84%	17,82%	7,15%	3,33%	7,94%	18,01%	7,24%
C (C_n=3)	3,71%	14,73%	35,41%	14,32%	3,71%	15,13%	35,84%	14,74%
D (C_n=4)	4,77%	30,16%	78,59%	29.93%	5,24%	30,82%	78,30%	30,53%
E (C_n=5)	3,54%	49,10%	113,07%	49,22%	4,13%	50,32%	117,79%	50,40%

One can notice 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 for FPM even though smaller than RPM.

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

Rigid Platform Model - 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%
Flexible Platform Model - 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)	1,90%	2,78%	6,73%	2,04%	1,95%	2,79%	6,19%	1,99%
B (C_n=2)	1,08%	3,97%	11,23%	3,97%	1,19%	4,07%	11,44%	3,91%
C (C_n=3)	2,93%	8,94%	22,18%	8,48%	3,29%	9,23%	23,15%	8,67%
D (C_n=4)	3.09%	14,26%	47,99%	13,99%	3,97%	14,91%	50,04%	14,44%
E (C_n=5)	0,02%	32,56%	81,76%	32,72%	0,34%	32,84%	80,78%	33,00%

4 Conclusions

For a greater speed of passage of vehicles in platforms systems, errors are increased as expected. The increase of the RMS error occurred linearly as a function of the speed for the range of 10 to 80 km/ h tested for both types of vehicles for both the rigid and flexible platform models. For the standard deviation, similar behavior was observed. Weighing at very high speeds using only one platform becomes complicated because higher speeds mean little acquisition time for a fixed size platform and this makes it difficult to accurately assess the weight. Step height variations on low maintenance weighing platform systems can lower the maximum speed for weighing measurement and therefore accuracy using the WIM system. It was observed that a good linear adjustment of the step as a function of the mean error of the PBT and the axes in the range of - 8 mm to + 8 mm simulated. For negative step values (below the average level of the lane) the measured weight was below the static and for positive values the measured weight was higher than the reference, this behavior is evidenced in practice. In this study an exponential adjustment of the pavement class was obtained as a function of the RMS error and the standard deviation obtained. As a rule, it has been noted that the use of very rugged road profiles such as classes D and E are not advisable in HS-WIM systems, as this will produce dynamic effects that will compromise accuracy in the measurement system (very high errors obtained for RPM and FPM).

The modeling of platform dynamics is important and affects the final weighing results, especially for type (b) vehicle, which has seen a considerable decrease in relative error values. For example, for the velocity of 40 km / h, class B track, platform step height of + 2mm was obtained RMS error 7.78% for RPM and 3.97% for FPM. It is envisaged that in the simulation of the weighing platform as completely rigid, the impact caused by the passage of the tires thereon is high by exciting the dynamics of the vehicle suspension and consequently generating fluctuations in the measured weight of the vehicle. While in the case of the simulation of the platform as flexible, this seems to have cushioned the impact and consequently the fluctuation of the force measured around the static weight of the vehicle. For specifically the same case mentioned above of speed of 40 km / h, class B, platform step height of + 2mm, a randomly identical RMS error of 7.84% was obtained for the RPM for the FPM. For a speed of 80 km / h under the same conditions of runway and step, the RMS error was 12.74% for the RPM and 12.00% for the flexible. This shows the importance of modeling the platform dynamics for both vehicles, especially a greater influence on the vehicle of type (b) causing the relative errors evaluated. However, in a few cases, this conclusion was not verified. For vehicle type (a) there were cases of small increase of the evaluated error of the error values depending on the test. It is thought that this may be related to the small mass, small wheel radius or type of suspension(independent). In the same condition of the above case, with a speed of 60 km/h, the RMS error was 9.75% for RPM and 10.87% for FPM.

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DESIGN OF A FEASIBILITY STUDY OF PORTABLE WIM SYSTEMS IN MANITOBA

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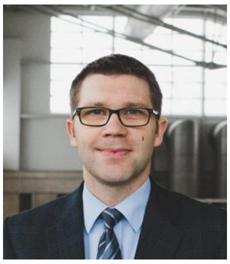

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Abstract

This paper describes the design of a study of the feasibility of a portable WIM system for axle load monitoring in Canada. Several previous studies and uses of portable WIM are discussed. The feasibility study comprises: (1) equipment selection criteria; (2) installation plans for two truck pairing surveys—one which compares the portable WIM data with static axle load data and the other which compares the portable WIM data with a high-speed piezo-quartz WIM system; and (3) analytical methods for conducting comparative assessments of the axle load data distributions produced by the portable WIM equipment. The significance of the paper lies in the potential for portable WIM systems to be used as an indirect source of axle load data, thereby improving the geographic coverage of axle load monitoring programs. Additionally, to our knowledge, the study will be the first of its kind conducted in Canada.

Keywords: Weigh-In-Motion, WIM, Portable WIM, Study design, Data collection

Résumé

Ce document décrit la conception d'une étude de faisabilité d'un système de pesage portable pour la surveillance de la charge par essieu au Canada. Plusieurs études et utilisations antérieures du WIM portable sont discutées. L'étude de faisabilité comprend: (1) des critères de sélection des équipements; (2) des plans d'installation pour deux enquêtes de couplage de camions, l'une comparant les données WIM portables à des données statiques de charge à l'essieu et l'autre comparant les données WIM portables à un système WIM piézo-quartz à grande vitesse; et (3) des méthodes analytiques pour effectuer des évaluations comparatives des distributions de données sur la charge par essieu produites par l'équipement WIM portable. L'importance du document réside dans la possibilité que les systèmes WIM portables soient utilisés comme source indirecte de données sur la charge à l'essieu, améliorant ainsi la couverture géographique des programmes de surveillance de la charge à l'essieu. De plus, à notre connaissance, cette étude sera la première du genre au Canada.

Mots-clés: Pesage en marche, WIM, Portable WIM, Etude de conception, Collecte de données.

1. Introduction

Weigh in motion (WIM) systems are used in Canada and around the world for monitoring vehicle weights on highways. The weight data collected from WIM systems can be applied in various ways, including direct enforcement of weight restrictions, pre-screening for enforcement of weight restrictions, freight demand modelling, and as direct inputs to the design of highway structures including bridges and pavements (Haugen, et al., 2016).

Many jurisdictions collect WIM data for use as direct inputs to pavement design, which shapes the processes by which WIM sites, equipment configurations, and data formats are selected as well as the standards by which WIM data quality are measured (Federal Highway Administration, 2018). For example, in Manitoba, Canada, the data requirements of the Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2015) motivated initial efforts to provide axle load data in 2010. These initial efforts relied on data produced by a network of six piezo-ceramic WIM systems. Subsequent research has focused on improving data validity (accuracy and precision) and the geographic representativeness of the axle load data. Additionally, new piezo-quartz sensors have been evaluated and are currently replacing piezo-ceramic sensors (Wood, 2017).

The MEPDG exists to provide pavement design engineers with tools to guide decision making in pavement design and rehabilitation. In doing so, it specifies that vehicle weight values should be in the form of full axle load spectra for each axle type, as well as identifying required vehicle sample sizes. Additionally, the MEPDG specifies three levels of data quality with which to classify road segments:

- Level 1: Weight data is available from a WIM site on or nearby the segment of interest
- Level 2: Weight data is available from a WIM site on a similar segment in the same region
- Level 3: No level 1 or 2 weight data are available, so default loading values may be applied, if available in the jurisdiction (AASHTO, 2015).

The benefit achieved by having level 1 and 2 data, which are preferable for use as direct inputs to pavement design, have led various jurisdictions in North America to investigate methods for obtaining high-quality WIM data over a wider geographical coverage, including the development of a portable WIM system that can be installed for 1 or 2 week periods by attaching WIM sensors to the road surface in order to gather weight data that would be suitable for use as direct inputs to pavement design (Faruk, et al., 2016; Kwon, 2012; Refai, et al., 2014). However, these studies have revealed that portable WIM systems cannot be relied upon to produce data that is accurate enough to use as direct inputs to pavement design (Faruk, et al., 2016; Refai, et al., 2014; Selezneva & Von Quintus, 2014), and level 3 data is still required as a design input in many cases.

In order to improve the quality of data available on level 3 segments, it would be possible to model the expected axle loads on a segment based on surrounding land use, nearby industries, applicable weight regulations, and climatic factors. A model that incorporates these, and potentially other, easily available data sources could have the potential to be far more accurate than the default values provided by the MEPDG. Little study has been devoted to developing such a model, with much of the existing research focusing on modelling truck volumes, rather than weights (Reimer & Regehr, 2013; Kulpa, 2013). Some efforts have been made to model weights by performing cluster analyses of existing WIM sites with a goal of assigning weight data to level 3 road segments in appropriate cluster groups (Haider, et al., 2011). However, to implement this approach, enough axle load data must be collected at each site to assign that site to a cluster group. It would be cost prohibitive to gather this data through the installation of permanent WIM systems, but potentially feasible to gather this data with a portable WIM system, which collects data with lesser temporal coverage and accuracy, but with greater geographic coverage. This study will examine a portable WIM's suitability for collecting data intended for use as indirect inputs to pavement design.

2. Past Studies of Portable WIM

Historically, studies of the capabilities of portable WIM systems have treated them as a potential source of MEPDG level 1 data and examined their potential for use as direct inputs to pavement design. These studies, conducted throughout North America, have found that portable WIM systems are a low-cost alternative to permanent WIM systems that can produce quality data, but have several key issues with their operation that limit their practicality.

Several prominent studies into portable WIM systems have been done in Minnesota (Kwon, 2012; Peterson, 2015), Oklahoma (Refai, et al., 2014), and Texas (Faruk, et al., 2016), having several key similarities and differences. Though each study used a different WIM controller, and a different method to attach the sensors to the pavement, all three used piezoelectric Roadtrax BL sensors. The Minnesota study included 20 installations, the Oklahoma study 3 installations, and the Texas study 1 installation; all 3 used the standard method of a pre-weighed test truck for calibration. Additionally, all three considered the effect of temperature on the axle load measurements, but only the Minnesota and Oklahoma studies compared the results with a permanent WIM system measuring the axle loads of the same sample of vehicles. Table 1 lists key findings from the reports.

Table 1 – Findings of Past Studies of Portable WIM in North America

Study	Findings
Minnesota (Kwon, 2012 and Peterson, 2015)	• The preferred duration of deployment is 2 days. • Temperature has no significant effect on load measurements. • The sensors achieved the GVW accuracy standard for ASTM Type II (±15%) for 90% of class 6 dump trucks and 93% of class 9 trucks. • Vehicle speed is positively correlated with load measurement due to the bump in the road created by the sensor.
Oklahoma (Refai et. al, 2014)	• The preferred duration of deployment is 4 days. • Temperature had a significant effect on load measurements • GVW measured by portable systems had 29% overall error compared to permanent systems. • Incorrect installation can allow sensor vibrations that can cause error. • Calibration with a test vehicle is necessary for every installation.
Texas (Faruk et. al, 2016)	• The preferred duration of deployment is 7 days • Sensors become significantly less able to detect light vehicles over the course of a 7 day deployment

In addition to these studies, portable WIM has been implemented in data collection programs in various jurisdictions. In 2014, the state of Georgia had a program involving collecting axle load data from portable WIM systems, however the data were not intended for use in for pavement design, but rather for the FHWA Truck Weight Study (FHWA, 1995); as such they were not calibrated according to the ASTM standard. At the same time, Montana, Utah, and Wisconsin were all using portable WIM to collect lower quality data that were to be used to select a default axle load spectra to apply to a site (Selezneva & Von Quintus, 2014). Despite this use, past studies have not explored how portable WIM may best be used towards indirect inputs to pavement design. Furthermore, despite the existence of several studies and extensive use of portable WIM in the United States, no major studies exist in the context of Canadian climate, truck classification distribution, and traffic volumes.

3. Design of Portable WIM Study

This study is designed to address the lack of investigation into portable WIM in a Canadian context and as indirect inputs to pavement design. In order to investigate these knowledge gaps, the study will be done in two phases. First, the portable WIM system will be installed alongside an existing static weigh scale to obtain ground truth accuracy of the system across a wide variety of vehicle weights and classes. Second, the portable WIM system will be installed alongside an existing permanent WIM system to compare accuracy of the two sensors across a large vehicle sample size. In doing so, the study will obtain a sample of ground truth data greater than which could be obtained by a calibration truck, which typically only perform 10 to 20 passes of a portable WIM site in order to properly calibrate the system (Faruk, et al., 2016; Refai, et al., 2014; Peterson, 2015). The test will reference the procedures and guidelines set out by ASTM E1318; the European standard, COST 323, will also be considered.

3.1 Portable WIM Equipment

The portable WIM equipment was selected with the two goals of system performance and cost minimization. This resulted in using components that are recommended for use in portable WIM applications both by past studies of portable WIM and by the equipment supplier, as well as placing an emphasis on components that were already in Manitoba Infrastructure's (MI) stock due to their use in MI's current permanent WIM data collection program. Table 2 lists the components selected for use in the study.

Table 2 – Portable WIM System Components

Component	Model	Number Required	Total Cost (CAD)	Expected Lifetime (Years)
WIM controller	IRD iSINC Lite	1	18500	>20
WIM sensors	Piezoelectric Roadtrax BL	4	4100	Unknown
Power supply	Manitoba Hydro (From grid)	1	-	Indefinite
Installation method	Pocket tape	1 roll (60')	112.50	Single use
Temperature probe	Not yet determined	1	~450	Unknown

The iSINC Lite WIM controller from International Road Dynamics was chosen as it is the current WIM controller being installed at new permanent WIM sites in Manitoba, and has been used in the portable WIM study conducted in Oklahoma in 2014. The piezoelectric Roadtrax BL sensors have also been used in all of the previous studies mentioned in section 2; piezoelectric sensors were selected due to the focus on their use in past studies. Though the power supply will likely be replaced with a solar power unit in any future applications due to the portability requirement, this study will draw from the Manitoba Hydro power grid as it is easily available at both sites of the test. Pocket tape has been selected as the method of attaching the sensors to the pavement due to the low cost of the tape, its previous use in the portable WIM study in Texas in 2016, and its ability to be implemented without further research into a new method of attaching the sensors to the pavement. The model of the temperature probe has not yet been determined as Manitoba Infrastructure only currently uses temperature probes that are installed in the pavement and cannot be easily moved; further study into an appropriate temperature probe is required.

The equipment will be installed as illustrated in Figure 1. This follows the installation guidelines outlined in the Federal Highway Administration's Weigh-In-Motion Pocket Guide Part 2 (Federal Highway Administration, 2018).

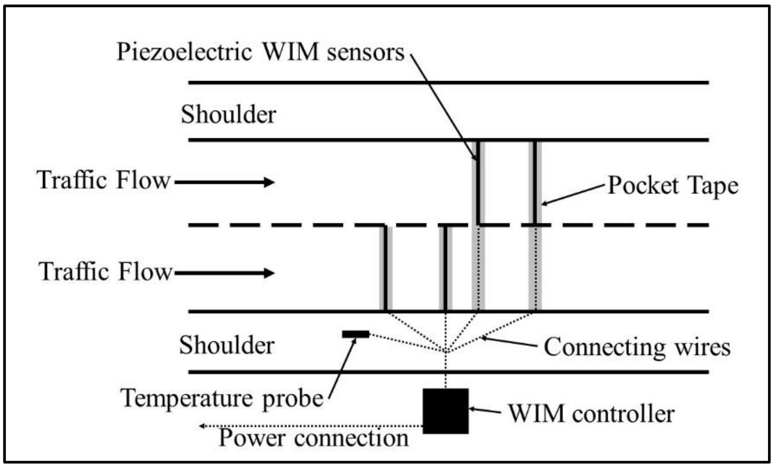

Figure 1 - Portable WIM System Equipment Configuration

3.2 Installations

This study will consist of two installations, the first installation next to a permanent weigh scale and the second next to a static WIM site. The weigh scale installation's data will be used to determine ground truth accuracy of the portable WIM sensors, and the permanent WIM installation's data will be used as a larger comparison data set. Additional installations at permanent WIM station 99 will be done at the availability of personnel, time, and resources to do so, in order to not only obtain more data for measurements of overall accuracy of the portable WIM system, but to test the system's performance in a variety of real-world weather and temperature conditions. Weather conditions will be recorded manually for each installation.

If used as part of a portable WIM system data collection program, the portable WIM sensors will be installed and removed from sites frequently. Therefore, it is important to develop a proper process for installing the sensors and evaluate its effect on the accuracy of the sensors. This has not previously been examined in an installation using pocket tape as the method of attaching the sensors to the road surface. Due to this, the required installation time for the sensors is not known, though it is likely that there will be a decrease in installation time from the first installation through later installations.

3.2.1 Installation at Headingley Permanent Weigh Station

The first installation will occur near the Headingley Permanent Weigh Station in Headingley, Manitoba. The Headingley weigh scale has been selected for this installation due to its convenient location 7 km west of the city of Winnipeg and its long hours of operation, which will benefit the data collection process.

The portable WIM system installation at the Headingley weigh scale is illustrated in Figure 2. The portable WIM will be located approximately 450m west of the weigh scale and office. The westbound direction was chosen in order to allow trucks to accelerate to a regular highway speed before crossing the portable WIM sensors; the eastbound direction approaches the town of Headingley and requires slower speeds. Furthermore, the acceleration lane from the weigh scale lane to the regular highway lanes ends approximately 450m from the scale, and by locating the portable WIM system west of this point, every truck that passed through the scale can be ensured to pass over the portable WIM sensors. Additionally, by locating the installation downstream from the weigh scale, the time in between the weighing on the static scale and the axle load measurement by the portable WIM will be more consistent and allow for more consistent truck pairing due to the elimination of the effects of truck queuing at the scale.

Figure 2 - Map of Portable WIM Installation at the Headingley Permanent Weigh Station

Active data collection will be necessary at this site as the province of Manitoba only records and stores truck weights at enforcement scales in the case that a citation is issued to an overweight truck. The active data collection process will consist of two personnel recording at each time. One person will be located in the scale office where axle group weights can be read off of a digital display and manually entered in a spreadsheet that timestamps each truck entry. Recorded characteristics of each truck will be: axle configuration, body type, distinguishing characteristics, and weights of each axle group. The second person will be located by the portable WIM site, entering the same data into a second spreadsheet without the weights and with a second timestamp.

The portable WIM installation at the Headingley weigh scale will remain in place for 14 days or until the installation is unable to collect data of any quality due to normal wear or sensor damage. Collection of static scale axle group weights will occur for 12 hours periods to a minimum of 48 total hours of data collection.

3.2.2 Installation at Permanent WIM Station 99

The second installation location will occur near permanent WIM station 99 located in Winnipeg, Manitoba. This station, located on Centreport Canada Way which is a 4-lane divided highway, has piezoquartz WIM sensors installed in the westbound drive lane and AVCs installed in the westbound passing and eastbound lanes. Station 99 has been selected for this installation due to its convenient location inside the city of Winnipeg as well as the higher data quality that can be obtained from piezoquartz sensors compared to the piezoelectric sensors that are used at most other WIM sites in Manitoba.

The portable WIM installation at permanent WIM station 99 is illustrated in Figure 3. The portable WIM system will be installed approximately 50m west of the permanent WIM station in the westbound lanes. This location was selected due to the presence of WIM sensors only in the westbound drive lane; additionally, a downstream location was selected due to the possibility that the bump created by the portable WIM installation could influence the axle load measurement by the permanent WIM station if placed upstream. The 50m distance between the two sites ensures that the portable WIM system will not interfere with the function of the permanent WIM station.

Figure 3 - Map of Portable WIM Installation at permanent WIM Station 99

The installation and calibration of the portable WIM will be scheduled to coincide with the calibration of WIM station 99; this will save on the cost of the two calibrations and ensure that the permanent WIM station is measuring as accurately as possible during the portable WIM installation. The portable WIM will be left installed for 14 days or until the installation is unable to collect data of any quality due to normal wear or sensor damage. During this time, the portable sensor will be inspected daily to monitor sensor wear.

3.3 Analytical Methods

The data analysis for this study will be divided into two parts, each corresponding to one of the portable WIM installation locations. The steps for each analysis will be the same, though the analysis of static scale data will give the true accuracy of the portable WIM system, while the analysis of the permanent WIM station data will report the accuracy relative to that type of system. The comparison data set (CDS) is the static weigh scale data for the first part, and the permanent WIM station data for the second part. The steps for each analysis will be:

1. Pair trucks from the CDS and portable WIM data using a combination of automatic algorithms and manual processing. Truck weight records will be automatically paired if they have the same axle configuration and a difference in time stamps that falls within a prescribed range. Given the close proximity of the portable WIM system installations to the static weigh scale and permanent WIM system, it is expected that this method will be sufficient to capture virtually all of the truck record pairs. If this method proves to be insufficient for the static weigh scale installation, it will be supplemented with manual pairing based on the recorded distinguishing characteristics.
2. Clean the data by removing erroneous results. Erroneous results will be those with unreasonably high or low axle weights, with the accepted lower axle load limit being 1500 kg and the accepted upper axle load limit being 150 percent of the axle configuration's allowable load limit. Any vehicle records with one or more axle groups removed by this process will not be used in the analysis.
3. Divide the data from both portable WIM data and CDS into bins, each consisting of a single day of the installation.
4. Calculate the accuracy of the portable WIM sensors in each bin to determine the accuracy over time and preferred deployment duration for collection of data for direct application to pavement design. These accuracies will be evaluated with reference to ASTM E1318 and COST 323, but the exact accuracy standards will not be used, as the standards assume that the accuracies are determined using a test vehicle, while the accuracy of the portable WIM system will be determined with reference to static scale and permanent WIM data that is itself subject to some error. These accuracies will be calculated for axle group loads and gross vehicle weights. The preferred deployment duration will be determined by the number of days of installation before the portable WIM system no longer records axle group loads and GVWs with sufficient accuracy.
5. Calculate the calibration drift of the sensors by comparing the front-axle weights of the class of vehicle used for calibration for the portable WIM and CDS for each of bin. As the front axle weights of the vehicle class used for calibration will be accurately recorded by the portable WIM system at the beginning of the installation due to the calibration process and the low variability of front axle weights, comparison of these axle weights over the days of installation bins will reveal how many days it takes the portable WIM system to fall out of calibration. A change of 5% or greater in the average front axle weight will be considered to be out of calibration (Selezneva & Wolf, 2017).
6. Prepare Axle Load Spectra and GVW distributions for each axle configuration for each data bin and for the year in the case of the permanent WIM system.
7. Apply a Gaussian Mixture Model (GMM) procedure to each distribution to distinguish empty, partially loaded, and fully loaded vehicles for each body class group. A GMM is a

linear combination of multiple normal distributions that are combined using a mixing parameter; applying a GMM to axle load data allows a single axle load spectra to be separated into multiple normal distributions, each representing a separate loading scenario (Hernandez, 2017). Ultimately, the shape of these distributions will help characterize loading patterns in a way that lends itself to summary and comparison of axle load spectra.

8. Calculate the mean and standard deviation of each loading scenario for each axle group type and vehicle configuration for each distribution.
9. Perform steps 6-8 on the overall CDS – all data collected over the installation period from both the static scale and the permanent WIM station.
10. Perform T-tests comparing the values of each loading scenario for each axle group type and vehicle configuration for each distribution. The results of this comparison – the number of T-tests that accept the two means as the same and the level of significance at which they do so – will indicate the level of similarity between the axle load spectra, and thus the overall accuracy of the portable WIM system.

In order to investigate whether sensor reliability, and therefore preferred deployment duration, correlates more closely to number of vehicle passes rather than elapsed time, steps 4-9 will be repeated on new bins that will be calculated based on number of vehicle passes over the portable WIM sensors rather than time elapsed. Additionally, in order to investigate whether the effects of temperature are likely to make portable WIM data unusable for indirect application to pavement design, steps 4-9 will again be repeated on new bins calculated from both deployment duration and recorded temperature.

4. Concluding Remarks

This study will be significant in that it will provide a detailed analysis of the accuracy of a commercially available portable WIM system in a Canadian context, presenting results derived from a significant sample size of both static scale and permanent WIM station data and giving particular consideration to the potential of the portable WIM data for use in indirect application to pavement design. This study will be able to provide an introductory guide for the implementation of portable WIM systems in Canada by examining issues with and best practices concerning installation and calibration of the sensors. Additionally, the analysis of axle load measurements will obtain:

- The overall accuracy of the portable WIM system (from analysis step 4),
- the calibration drift of the portable WIM sensors (from analysis step 5),
- the portable WIM data's suitability for selecting generic ALS and GVW distributions to assign to a location (from analysis step 9), and
- a preferred deployment duration for portable WIM systems.

These results will indicate whether the tested portable WIM system is suitable for direct inputs to pavement design, indirect inputs to pavement design, or neither. Further study will be required to design a process by which to sample sites with portable WIM to generate direct inputs for pavement design or a process by which portable WIM data can be used to assign a generic ALS or GVW distribution to a site.

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Session Posters

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Argentinian Technical Requirements and Evaluation of WIM Systems
Ignacio MORETTI, Javier Alejandro JORGE, José AMADO, Julian JONES

WIM site selection based on mutliparameter analysis
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Advanced Bridge Safety Applications of WIM Data
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Using Smart Materials for Weight in Motion, Nanowim
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ISWIM WIM User Guide
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Weigh-in-free-flow by OptiWIM
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Fatigue life assessment with WIM data and strain measurements
Ricardo MALDONADO, Mariia NESTEROVA, Franziska SCHMIDT, Guadaloupe-Moises ARROYO-CONTRERAS, Bernard JACOB

End-users Workshop

End-users Workshop 1 : Transport Efficiency & Safety

Chair: Chris Koniditsiotis (TCA, Australia)

Daniel Kneubuhl (Haenni) - *Weigh the loads and save the roads!*

Tamas Berzsenyi (IRD) - *Improving road safety using Tire Anomaly Detection and Weigh in Motion*

Jan Fucik (Camea) - *CAMEA WIM: Unique Customer Solutions*

Eric Peterson (Intercomp) - *Sensors and Stability: Performance with low cost ownership*

Christiaan Schildhauer (Mikros) - *Assuring continuous Data integrity every step of the way*

End-users Workshop 2 : Advanced Weight Enforcement

Chair: Bernard Jacob (IFSTTAR, France)

Zhao Zhai(Vanjee) - *All-inclusive WIM Direct Enforcement system collects complete chain of traffic legal evidence to regulate overloaded truck*

Tomáš Juřík (Cross) - *OptiWIM - New WIM Capabilities and Applications Enabled by Fibre-Optic Technology*

Stefan Daxberger (Kapsch) - *WIM integration into Electronic Tolling*

Benoit Geroudet (Sterela) - *Approach of the Walloon Public Service for WIM direct enforcement*

Florian Weiss (TDS) - OIML R134 certification of WIM systems

End-users Workshop 3 : Infrastructure Design & Maintenance

Chair: Aleš Žnidarič (ZAG, Slovenia)

Colin Reekie(Q-Free) - *Weigh in Motion - For Asset Monitoring and Education (Prevention is better than cure)*

Matija Mavric (Cestel) *An innovative way of using Bridge WIM data*

Tomas Pospisek (Kistler) - *Effective protection of bridges against overload: use case from Mexico*

Richard Brown (TE) - *RoadTrax BL: Over Two Decades*

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