Back

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The International Scientific Committee wishes to thank the sponsors of the Fourth International Conference on Weigh-In-Motion (ICWIM4):

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Preface

The ICWIM conference series began in 1995 in Zürich, Switzerland, as a dissemination activity of the European Commission sponsored coordination action, COST 323. In the ten years since that time, there have been two other conferences, Lisbon, Portugal, in 1998 and Orlando, USA, in 2002. The conferences are now truly international with the success of ICWIM4 in Taiwan.

The original COST 323 group completed its work in the 1990's but Weigh-in-Motion continues to develop and grow. There has been a great deal of progress over the years and today's WIM systems are considerably better than those reported in Zürich. The independent tests of commercial and prototype systems carried out under the supervision of the COST 323 group gave clients a good indication of what could be expected from field installations. The COST specification was developed to provide a standard method of calibration and testing and to define a framework for the classification of WIM system accuracy.

The ICWIM conferences are useful benchmarks of where the technology is at and where it is going. A wide variety of papers have been presented and published reflecting the interests of delegates. Some papers report on academic studies – new algorithms for the improvement of accuracy for example – while others report on experience in the field or on the use of WIM data for applications as wide-ranging as bridge assessment or the planning of motorway rest areas. Together the proceedings volumes constitute an invaluable resource for those working with WIM and bring together reports of best-practice from around the world.

ICWIM4 is a valuable update of the situation in 2005 and will show where WIM is going in the future. There are many exciting developments emerging. WIM seems likely to be combined with other sensor technologies in integrated Intelligent Transportation Systems (ITS). Truck weight data may be combined with speed and distance sensors to warn drivers if they are too close to the vehicle in front (braking distance is a function of weight) or if they are at risk of rollover. WIM is likely to be used to provide aggressiveness indices for roads and bridges and network managers will be able to have real-time monitoring of the remaining service life of the infrastructure in their care.

In 2005, the WIM industry seems to be on the brink of a new era of growth and development as the direct overload enforcement application comes of age. This has been discussed in the past and an early application from Taiwan was reported at a past conference. However, the widespread use of WIM for direct enforcement of overloaded trucks seems likely before the next ICWIM conference. Considerable progress from the Netherlands is reported in this volume and plans for a direct enforcement application in France. If these pilot projects are successful, others will quickly follow and demand for WIM technology will be stronger than ever when this group meets again in Paris in 2008.

Chia-Pei CHOU	**Eugene OBRIEN**	**Bernard JACOB**
Chairperson of the 4th International Conference on WIM	*Chairperson of the International Scientific Committee*	*Vice-Chair of the International Scientific Committee*

Panel Discussions & Concluding Presentation

Two panel discussions were held during the conference, the output of which are reported in this CD and in this document. A Conclusions paper, presented by Prof. E. J. OBrien, is also included herein.

Panel Discussion N°1: Use of WIM data as a tool for enforcement

Chairperson: R. HennyCo-chair: C-P. Chou

Panelists:

Chia-Pei Chou, TNU, Republic of China (Taiwan)
Mark Gardner, Fugro Consultants LP, United States of America
Ronald Henny, DWW, The Netherlands
Bernard Jacob, LCPC, France (on behalf of **Yves Marchadour**, Ministry of Transport)
Chris Koniditsiotis, Austroads, Australia & New Zealand
Hans van Loo, DWW, The Netherlands
Ralph Meschede, BAST, Germany

The panel discussion considered the state-of-the-art and current developments in the application of WIM to the pre-screening, enforcement and control of overloaded vehicles. Technical and legal issues were discussed, as well as implementation questions.

Panel Discussion N°2: New applications of WIM (incl. Railways)

Chairperson: E.J. OBrien   Co-chair: G. DenBuurman

Panelists:

Victor Dolcemascolo, LCPC, France
Hendrik-Jan de Graaf, NedTrain Consulting, The Netherlands
Gerlof Den Buurman, ProRail, The Netherlands
Gerard James, Royal Institute of Technology, Sweden
Eugene OBrien, UCD, Dublin, Ireland
Barbara Ostrom, MACTEC Engineering and Consulting, Inc., United States of America
Lily Poulikakos, EMPA, Switzerland
Aleš Žnidarič, ZAG, Slovenia

The panel discussion considered recent developments and emerging applications of WIM, including Railways WIM. The expressed and future needs for WIM data were discussed.

Conclusions

E.J. OBrien, UCD, Dublin, Ireland

Highlights are presented of papers presented and views that emerged in Session and Panel Discussions. Predictions are made for the state-of-the-art that will exist in the 5th conference planned for 2008.

Table of Contents

Session 2 - Railway WIM

Chairperson: A. Žnidarič   Co-chair: V. Dolcemascolo

Session 3 : WIM data quality, application to traffic management and road safety

Chairperson: B. Jacob   Co-chair: C. Koniditsiotis

Session 4 - Use of WIM data as a tool for enforcement

Chairperson: C-P. Chou Co-chair: H. van Loo

Session 5 : Application of WIM to Infrastructure (pavements and bridges)

Chairperson : L. Poulikakos, Co-chair : A. González

ICWIM4 Conclusions
E. O'Brien

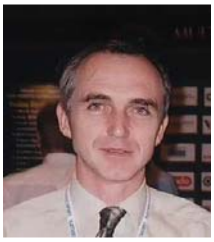
SESSION 0 :

INTRODUCTORY SESSION

Chairperson: Eugene O´Brien

WEIGH-IN-MOTION : RECENT DEVELOPMENTS IN EUROPE

Head of Traffic Monitoring, Road Operation, Signs and Lighting Department at LCPC. Chair of COST 323 (WIM), co-ordinator of WAVE project, Chair and vice-chair of Scientific Committees of 1st, 2nd and 3rd WIM conferences.



Professor of Civil Engineering at University College Dublin, Ireland. Vice-chair of COST323 (WIM), delegate for COST345 and COST341. Member of WAVE and SAMARIS projects. Member of Scientific Committees of 1st, 2nd and 3rd WIM conferences.

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Ireland

Abstract
This paper provides a review of recent European developments in WIM. Pan-European and national projects are reported plus developments in sensor technologies and system design. Recent developments in multiple-sensor WIM systems are given particular attention. The coming of prototype fully-automatic overload systems is discussed and the technologies and legal framework necessary for their success. The commercialisation of Bridge WIM in Europe since the ICWIM3 is considered and the continued development of this technology towards almost maintenance-free systems. WIM applications are also discussed including pavement and bridge design and assessment.

Keywords: Weigh-in-Motion, WIM,

Résumé
Cet article donne un panorama des récents développements du pesage en marche en Europe. Il présente les principaux projets européens et nationaux et les développements technologiques concernant les capteurs et la conception des systèmes. Les travaux récents sur le pesage multi-capteur sont examinés plus particulièrement. L'introduction de systèmes prototypes pour automatiser le contrôle des surcharges est discuté, tant du point de vie des technologies à mettre en œuvre que du cadre légal nécessaire à leur usage. La commercialisation de systèmes de pesage par pont instrumentés en Europe a débuté depuis la conférence ICWIM3 et les développements se poursuivent pour tendre vers des systèmes ne nécessitant pratiquement pas de maintenance. Les applications du pesage en marche, notamment pour la conception et la vérification des chaussées et des ponts, sont aussi abordés.

Mots-clés: Pesage en marche,

歐洲動態地磅之發展現況

摘要：
此篇論文提供了歐洲在動態地磅 (Weigh-in-Motion, WIM) 最新發展的回顧。全歐洲及各國有關動態地磅之國家計畫均囊括在內，另亦包括感測器技術之發展和系統設計。而最受矚目的是目前正在發展的多重感測器動態地磅系統。文中亦探討全自動載重系統的雛型，其中科技之研發與法律相關架構則是絕對必要之重點。自第三屆國際動態地磅研討會以來，橋樑式動態地磅的商業化已在發展中，而此一系統正持續朝向零養護之方向發展。文中同時亦探討動態地磅於鋪面與橋樑設計與評估之應用。

關鍵字：動態地磅

1. Introduction

There have been considerable developments in the Weigh-in-Motion industry in Europe in recent years. In the past, WIM sensors lacked durability and there was a lack of consistency in methods of assessing accuracy. The COST 323 action from 1993 to 1998, brought together WIM users from across Europe and resulted in several improvements:

- a report on the WIM needs of the transport industry,
- independently monitored tests of commercial and prototype WIM systems,
- a WIM standard with a standardised accuracy classification method (COST323, 1999),
- two WIM conferences for dissemination of research results and sharing of information on WIM developments (Jacob 1995, Jacob & OBrien 1998).

The final report for the COST 323 project has now been published (Jacob et al. 2002 & 2004).

The 4th Framework WAVE project, 1996 to 1999, complemented the activities of COST 323 (Jacob 1999 and Jacob 2002). This project funded research at a number of levels and resulted in significant advances in several areas:

- new algorithms to process the output from multiple-sensor WIM systems,
- significant advances in Bridge WIM technology, both in accuracy and in the range of bridge types through which it can be implemented,
- prototype database and WIM data quality assurance procedures,
- independent testing of WIM systems (overseen by the COST 323 group), including a test in cold climates,
- development of a fibre optic WIM sensor.

The 5th Framework TOP TRIAL project, 2000 to 2002, focussed more on the system architecture for a full scale trial of an automatic weight enforcement system utilising WIM sensor arrays:

- a semi-automatic weight enforcement system was constructed and operated,
- WIM sensor reliability and accuracy were investigated
- simulation techniques were developed to determine an optimal sensor layout for a multiple-sensor site,
- a cost-benefit analysis was carried out of alternative approaches to overload enforcement.

Since the 3rd International Conference on WIM, ICWIM3 (Jacob et al. 2002), the emphasis has shifted in Europe. There is increasing interest in semi-automatic systems for overload enforcement and a push towards fully automatic systems. Sensor design continues to progress and new technologies are still emerging. Bridge WIM has undergone considerable development and there has been a shift in focus from the laboratory into the field. There have been no pan-European WIM research projects in the past few years but there are a number of bilateral collaborations, and an on-going project on automatic weighing of trucks for enforcement: REMOVE (Requirements for EnforceMent of Overloaded Vehicles in Europe).

2. WIM for Pre-screening and Enforcement of Overloads

2.1 Video-WIM in the Netherlands

Some of the most significant recent developments in European Weigh-in-Motion have been the Dutch WIM-NL and WIM-Hand projects (van Doorn, 2000; van Loo, 2004). In WIM-NL (van Saan & van Loo, 2002) pre-selection applications of WIM were constructed which utilise video images of overloaded trucks to assist their identification. The WIM system identifies overloaded trucks and generates a video image which is transmitted to personnel at a static weigh station downstream in the traffic. The measurements and the image are also sent to the Traffic Inspectorate for company profiling and preventive activities. Piezoquartz strip sensors are used for this application.

WIM-Hand is an abbreviation for "Weigh-in-Motion voor directe Handhaving" (direct enforcement) and its primary goal is to show that Weigh-in-Motion technology can be used for the automatic enforcement of overloaded vehicles. Problems with the hardware and the calibration of sensors in the multiple-sensor array have prevented the achievement of any reliable measurement results to date. To bridge the interval until fully automatic direct enforcement is possible, DWW have installed six operational video systems for pre-selection with an additional 2 systems in 2005 and there are plans to upgrade them to fully automatic enforcement systems in the future.

2.2 Overload Control Project in France using WIM

Since 1996 the Ground Transportation Division (DTT) of the French Ministry of Transport has supported R&D on: (i) Low-Speed (LS-)WIM, (ii) Multiple-Sensor (MS-)WIM, and (iii) Video-WIM. This work is carried out by the Laboratoire Central des Ponts et Chaussées (LCPC) and the CETE de l'Est, jointly with some manufacturers. The need for automatic systems for overload pre-screening and enforcement was identified because of the rapid increase in heavy goods vehicle density, a trend towards more overload cases because of strong competition in freight transport and a reduction in human resources for control, i.e., weighing officers and police staff (Marchadour, 1998).

A LS-WIM system was developed by a company and successfully tested in 1998 (Dolce-mascolo et al., 1998). The system met accuracy class A(4) according to the COST323 Specification and OIML class 10 (OIML, 2004). A certification procedure for this system is under completion by the French Legal Metrology authority, and an additional test was carried out in early December 2004, which proved that the system has slightly improved since 1998. It is expected that such a system may be used for enforcement instead of static wheel and axle scales in the near future.

Since 2001, the DTT has experimented with two WIM systems, associated with video and automatic vehicle plate recognition, in order to screen vehicles that are suspected of being overloaded or of speeding (Stanczyk and Marchadour, 2005). The DTT plans to implement in 2005-2007, a network of 20 to 40 Video-WIM systems linked to a telecommunication network (either the common telephone network, an ADSL network or a dedicated network, such as fibre optic on motorways). The WIM systems are to be installed on highways and motorways throughout France, close to enforcement areas. During enforcement periods, the system will send a picture of the suspected violators to the enforcement staff a few km downstream, and the vehicles will be stopped either at a toll station or using variable message signs and police staff. In addition, the system will record pictures 24/7 of suspected violators, in protected and legally registered files, which will be used later by the DTT to focus control on the companies which accumulate most suspected violations. A European call for tender was issued in Summer 2004, and the contract for a first phase of at least 10 systems will be signed in Spring 2005. The LCPC and CETE de l'Est were appointed by the DTT to help with the specification of the whole system, to choose the required sites and later, to perform the acceptance tests of the systems. The specification does not require any particular technology for the WIM sensors, but the design of the system requires two WIM strip sensors per traffic lane.

2.3 Overview of Overload Control in Germany

LS-WIM systems are already approved (by the PTB) in Germany for enforcement in specific areas. Video-WIM systems are or will be used for accurate pre-screening of overloaded vehicles prior to a static weighing system or a LS-WIM system. The bending plates used in the past are now being replaced either by piezoquarz strip sensors or by other types of marketed sensors. The Federal Highway Research Institute (BAST) is investigating new technologies.

Since 2003, Germany decided to implement a toll system for heavy goods vehicles (above 12 tonnes for the authorised GVW), based on the mileage of each vehicle across the country. GPS and AVI systems, as well as electronic toll cards are part of the whole system. WIM systems will obviously be necessary to check and monitor the HGV's which are subject to this charge. However, until now it seems that the system is not fully operational.

2.4 European REMOVE project

The REMOVE project (van Loo and Henny, 2005), coordinated by the National Police Agency of the Netherlands (KPLD), is a 6th Framework project funded by the European Commission Transport and Energy directorate, DG/TREN. It started in February 2004 and is planned for 2 years. The partners are: Euro Control Route (ECR), TISPOL (European Association of Transport Police), the German Ministry of Transport, Building and Housing (BMVBM), the Dutch Ministry of Transport (DWW), the LCPC associated with the DTT (France), and the International Road Transport Union (IRU). The project will directly contribute to the introduction and dissemination across the EU states of new technologies related to the process of automatic weighing of trucks.

In the few EU countries, where WIM has already been used to aid overload enforcement, it appears to be extremely effective. Although a number of technical improvements still have to be made and a legal framework has to be drawn up, WIM system are clearly more than just a way to check practically unlimited numbers of trucks for overloading. The modern electronic vehicle recognition systems and communications networks make it possible to build entirely new enforcement models. In the near future these models can be based on intelligence gathering because of the huge number of measurements that are made. These measurements will allow the enforcement agencies to distinguish between legally compliant and non-compliant transport companies. The compliant companies will be hindered less by enforcement activities, whilst the non-compliant ones can be the focus of more intensive enforcement activity. In this way, the enforcement agencies can deploy their staff much more efficiently.

WIM systems, connected to a communications network could easily be deployed at an international level. For example, information about overloading offences which are committed abroad, can be sent to the member state where the transport company is registered.
WIM systems, combined with new enforcement technologies should change the operational concepts of the enforcement agencies in the coming years. Harmonisation of such practices in Europe is also a focus.

3. Multiple-Sensor WIM

While LS-WIM is a significant improvement in efficiency over static weighing, the future evolution of enforcement efficiency will require High-Speed (HS-)WIM systems approved for overload control. This means that an accuracy class of A(5) according to the COST323 Specification must be definitively achieved. It is even likely that the required level of confidence will be higher than the minimum specified in the COST323 Specification, perhaps 98 to 99%. It means that for a given system and installation, instead of looking for the smallest confidence interval (δ_{min} in width) at a level of confidence of let say 95%, the approval will be given in a lower accuracy class (i.e. a larger δ or confidence interval width) but with a higher confidence.

Because of the dynamic effects induced in the trucks by the pavement profile, it has been shown['proven' is a bit strong] that no current pavement WIM system, using one or two sensors per lane, will be able to meet an accuracy class better than B(10) to C(15) on a very smooth pavement profile (Jacob and Dolcemascolo, 1998). However, there is considerable scope for accuracy improvement by combining several measurements of axle impact forces at different sections using a multiple-sensor WIM array. Force measurements are processed using simple averaging or more sophisticated algorithms, which can significantly reduce the inaccuracy of the static load estimation by WIM. Since the theoretical and experimental work done in the WAVE project (WP1.1), further investigations were carried out in France (Dolcemascolo et al., 2002; Labry et al., 2005a) and in Ireland using Neural Networks (Shamseldin et al., 2000; Black et al., 2002; González et al., 2002; González et al. 2003) and Functional Networks (González and O'Brien, 2005). New experimental programmes are planned in France and in the Netherlands. In the latter, a MS-WIM array of 16 rows of piezoquarz sensors has been installed on a motorway near Utrecht.

The critical problems to be solved in MS-WIM are mainly related to the individual sensor noise or inaccuracy. It was proven in the previous works and by simulations that with very accurate impact forces measurements and a number of sensors between 10 and 16, accuracy class A(5) can easily be met. Some accuracy improvement of piezoceramic strip sensors is expected if the lateral position of the wheels are measured and taken into account (Labry et al., 2005b). Afterwards, if the required accuracy is met, some additional issues will still have to be investigated and solved for legal applications and enforcement: (i) certification or approval of such HS-WIM systems by Legal Metrology Organisations, and (ii) reliability of the systems against violation or attempts to escape the control. For issue (i), the lack of International Standard approved by the OIML (the current OIML Recommendation's scope is limited to MS-WIM) will make it difficult to get approval for such HS-WIM systems. To ensure the reliability of HS-WIM based enforcement systems, it will be necessary to implement complementary traffic measurement tools, in order to identify vehicles trying to escape the control, e.g., by running between two adjacent traffic lanes, or partially on the emergency lane, or braking/accelerating on the sensors. MS-WIM systems with less sensors, e.g., 4 to 8 per traffic lanes, may be useful for other applications requiring an accuracy such as B(10) to B+(7). The main choice for the users is to decide between: (i) fewer sensors (i.e., 1 or 2) of high quality and cost, or (ii) more sensors (MS-WIM) of lesser quality and cheaper. Because of the dynamic effects induced by the pavement roughness, (ii) is clearly the best solution for average road profile pavements.

4. Bridge WIM

In the WAVE project, the accuracy of Bridge WIM systems was considerably improved and tested on a range of bridge types in Ireland and Slovenia (McNulty & OBrien, 2003; OBrien & Žnidarič, 2001). In ICWIM3, tests in Sweden were also reported and new techniques for automatic calibration of the system without the need for expert knowledge in Structural Analysis (Quilligan et al., 2002; Žnidarič et al., 2002). Since ICWIM3, there have been over 70 commercial installations of Bridge WIM systems in Slovenia, Sweden and in the Netherlands. In addition, the effectiveness of Bridge WIM has been demonstrated in Canada, Austria, Poland and Croatia. The electronic systems and the software that runs and evaluates the measurements have improved considerably as has the user interface. For example, the SiWIM system developed by ZAG and CESTEL can be fully controlled from a remote office through a mobile telephone connection. It also automatically sends warnings to the control centre in the case of exceptional events and can be used with a video camera, with or without licence plate recognition, to control and pre-select overloaded vehicles.

There is ongoing work on Nothing-On-Road (NOR) Bridge WIM in an effort to get away from the safety and cost implications of axle-detecting sensors embedded or placed on the road surface. Following the original successful work on orthotropic (Dempsey et al., 1998) and short slab bridges (OBrien & Žnidarič, 2001), considerable progress has been made on the extension of the NOR concept to other bridge types. The reliability of axle identification and axle spacing calculation has been increased to a level that NOR bridge WIM systems can now be used for regular measurement. In Slovenia, 20 bridges or around 50% of all installations in 2004 have been done in this way (Žnidarič et al., 2005). Bridge WIM is not been applied on bridges that would not previously have been contemplated, such as 30-m long beam-deck bridges. A new NOR Bridge WIM approach is reported in this conference (Dunne at al., 2005). This utilises wavelet techniques to transform the original strain signal in a way that highlights the effects of individual axles.

In France, an R&D project started in 2004, to be carried out by the LCPC for the DTT, with the objective to install and test Bridge WIM systems on several types of bridge (orthotropic decks, very short span bridges, multiple simply supported span bridges, slab or integral bridges). The SiWIM system, using the results of the WAVE project, will be installed and if necessary improved in cooperation with the Slovenian partners. The final goal is to include this technology in the pre-screening WIM system network described in section 2.2.

Bridge WIM systems are expected to be a suitable tool for pre-screening and enforcement of overloads, provided a convenient bridge for WIM is located near to the required site. Besides the improved accuracy (which already meets class A(5) for some bridges with very smooth pavement and the most advanced algorithms (Brozovič et al., 2005)), this system has other practical advantages: (i) it is impossible for a vehicle to avoid the WIM system if crossing the bridge, (ii) the system is not visible for the drivers, and much less exposed to vandalism than road sensor systems, (iii) the system may be installed and replaced without traffic disruption and in good safety conditions, which is important for busy motorways and heavily trafficked highway. However, it may be more difficult to get a type approval or certification for such a system from a legal metrology organisation, for a direct enforcement application. The reason is that the bridge is part of the measuring system and, as each bridge is different from the others, it could require a case by case approval.

5. Application of WIM for Infrastructure, Road Safety and Environment

Applications of WIM in Europe are currently focussed primarily on the enforcement of overloaded vehicles, with the underlying Commission goal of ensuring fair competition between transport modes and transport companies. However, other applications are still important such as road safety, infrastructure and traditional applications to traffic monitoring and statistics.

In the late 1980's and early 1990's, a great deal of work was carried out in which WIM data from several European countries (Jacob et al., 1989) formed the basis for the Eurocode, EC1, Part 3 (Traffic Loads on Road Bridges). The design loads were assessed using statistical extrapolation of load effects (Flint and Jacob, 1996) while fatigue loads were calibrated in order to ensure that bridge lifetimes were in agreement with expected traffic conditions (Jacob and Kretz, 1996). Since this initial work, some countries used local traffic measurement to calibrate the so-called α-factors which allow increases or reductions in some load intensities to account for region-specific conditions (Orr & OBrien, 1999; O'Connor & OBrien, 1997). In the past 2-3 years, some verifications were carried out using new traffic data to check if recent increases in truck volumes and gross weights are affecting bridge safety, mainly in fatigue (Jacob and Labry, 2002). Such verification was required to transform the pre-standard (ENV) into a standard (EN). In the future, it will be necessary to perform periodical checks (e.g., every 5 to 10 years), because of the upward trend in the maximum truck GVW in Europe. In Scandinavia GVW's of up to 60 tonnes are allowed and in the Netherlands up to 50 tonnes. In France some trucks (e.g., timber haulage or container in combined rail and road transport) are allowed to carry 44 tonnes. Increases in the portion of freight carried by vehicles at the upper ends of these legal limits as well as illegally overloaded vehicles are hugely important factors in determining the characteristic traffic loading on bridges.

In recent years, the emphasis has shifted from the design of new bridges towards the assessment of existing bridges (Grave et al., 2000). A review of European highway structure assessment procedures was conducted through the COST 345 action. The resulting report on state-of-the-art procedures for the assessment of bridge traffic loading is given by OBrien et al (2005). The implications of the accuracy of recorded WIM data and the duration of recording on the predicted load effect are assessed by O'Connor & OBrien (2005) along with the sensitivity of the extreme to the method of prediction. The effect of traffic evolution with time in terms of increased volumes of flow and weight limits are also explored.

There is some research ongoing on developing an improved understanding of the link between traffic loading and pavement deterioration (OBrien et al., 2004). However, there is a significant lack of experimental data. HDM-4 and the Swedish Pavement Management System study

emphasises that is very difficult to measure and describe the complexity of the road surface and its characteristics. Further, it must be technically possible and practically feasible to measure the indicator.
With the evolution of the truck design, e.g., more axles, 4-axle bogies, smaller wheel diameter, tractor with double trailer, etc., it will be important to re-assess the pavement lifetime against fatigue and the effects of new traffic patterns. WIM data on European main routes will be an essential tool to detect such changes in loading patterns and link them with changes in the rate of pavement deterioration.

Finally, road safety and environmental impact became top priorities in the EU and in most of the member states in the late 1990's and remain so. Monitoring truck load and speed is important to ensure traffic safety. Gas emission and energy consumption are also to be considered. The debate is still open to decide if more relatively light trucks or fewer heavier trucks are the more efficient in environmental and safety terms to satisfy future transport demand, projected to grow by about 40% in Europe over a 10 year period. WIM data providing an accurate survey of the real loads carried by European trucks will be necessary to quantify the impact of heavy goods road transport on the safety and environment.

6. Conclusions

Recent European developments in WIM are reviewed. There has been a considerable shift in emphasis towards accurate pre-selection and automatic enforcement of overloaded trucks. Fully automatic enforcement has not yet happened but seems likely to come in the near future. This seems likely to come from multiple-sensor WIM and there has been considerable activity in the construction of pilot systems and the development of new algorithms for combining the outputs from the sensors. Durability of sensors has continued to cause problems but seems to be improving.

Bridge WIM is progressing well. With axle detectors on the road surface, it is achieving good and improving levels of accuracy. For applications that require less accuracy, Nothing On Road Bridge WIM systems are under development with clear implications for improved safety during installation and maintenance.

In addition to the pre-selection and high-speed enforcement of overload applications, there has been progress on the use of WIM for accurate assessment of bridge loading. Pavement assessment and design is still at an early stage and seems likely to take some further years.

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NORTH AMERICAN WEIGH-IN-MOTION ACTIVITIES

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Abstract
This paper presents an update on weigh-in-motion (WIM) in the United States and Canada. It follows the paper "Weigh-in-Motion in North America" by Mark Hallenbeck and David Jones presented at ICWIM3 in 2002. A survey is presented of activities in WIM data collection, data management, enforcement, pavement design, and standards.

Keywords: Weigh-in-motion, WIM, Enforcement, Standards, Axle Load Spectra.

Résumé
Ce papier présente un état de l'art sur le pesage en marche (WIM) aux Etats-Unis et au Canada. Il fait suite à l'article « Pesage en marche en Amérique du Nord » par Mark Hallenbeck et David Jones a présenté à la conférence ICWIM3 en 2002. L'article présente les activités de collecte et gestion des données, leur application au contrôle des surcharges, à la conception des chaussées, et les normes sur le pesage en marche.

Mots-clés: Pesage en Marche, Contrôle, Normes, Histogramme de Charges D'essieux.

北美動態地磅發展現況

摘要：
此篇論文主要在於提出美國和加拿大目前在動態地磅 (Weigh-in-Motion, WIM) 方面的最新發展情形，並以 Mark Hallenbec 與 David Jones 於 2002 年第三屆國際動態地磅研討會中所提出的 "Weigh-in-Motion in North America"（北美動態地磅現況）進行後續討論。文章重點內容包括動態地磅應用於資料收集、資料管理、執法、鋪面設計和標準之概況說明。

關鍵字:動態地磅、執法、標準、軸重曲線

1. Introduction

In May 2002, ICWIM3 was held in Orlando, Florida, in conjunction with the North American Travel Monitoring Exhibition and Conference (NATMEC 2002). At that time, a paper was presented on "Weigh-in-Motion in North America". There have been many activities related to weigh-in-motion (WIM) in the United States and Canada since 2002. What follows is a survey of recent activities in WIM data collection, data management, enforcement, pavement design, and standards.

2.1 Standards

The Traffic Monitoring Committee of the standards organization ASTM International is developing several new standards. A "Standard Specification and Test Methods for Highway Traffic Monitoring Devices" is proposed as a general specification of the functions and data requirements of devices other than WIM systems, which are covered by standard 1318-02 ("Standard Specification for Highway WIM Systems with User Requirements and Test Methods"). A "Standard Practice for Installing Piezoelectric Highway Traffic Sensors" will cover the installation of piezoelectric roadway sensors that are used to detect axles used for counting, classifying, and weighing vehicles. Other standards under development cover axle count adjustment factors and installing pneumatic tubes for traffic counting.

2.2 Long Term Pavement Performance Project

The Long-Term Pavement Performance (LTPP) program began in 1987 as a comprehensive 20-year study of in-service pavements (see http://www.tfhrc.gov/pavement/ltpp/ltpp.htm). It covers a series of field experiments monitoring more than 2,400 asphalt and concrete pavement test sections across the U.S. and Canada. The LTPP has been a major impetus for collecting traffic load data from WIM in the U.S. and Canada since 1989. With the program in its final phase, there is a critical need to ensure that at least five years of traffic load data are available for LTPP experiments.

Twenty States have committed US$2.7 million in a pooled-fund study to improve the quality and quantity of traffic data from five of the LTPP program's Specific Pavement Study (SPS) projects. This five-year study consists of two phases: Phase I began in August 2003 and consists of assessing, evaluating, and calibrating the current WIM and vehicle classification systems used to collect traffic data at SPS sites. Phase II began in November 2004 and consists of procuring, installing, maintaining, and repairing WIM systems to ensure high-quality data collection.

The WIM sites shall conform to the user requirements of ASTM 1318-02, with the following exceptions:

- The pavement must be constructed of Portland concrete cement from at least 99 meters prior to and at least 23 meters following the WIM scale area; and
- Profiling of the pavement smoothness may be performed using a high-speed profiler.

The LTPP data are subject to an extensive series of quality control checks before being made available to the public. DataPave Online (http://www.datapave.com/) is a major effort to make the LTPP data more accessible to worldwide transportation community. The extensive database effort includes road inventory, materials testing, pavement performance monitoring, climatic, traffic, maintenance, rehabilitation, and seasonal testing modules. The LTPP database is the world's largest pavement performance database, with enormous potential for the development of products to improve pavement technology. However, the traffic and pavement profile data in DataPave are only summaries. For access to the raw traffic and profile data, contact LTPP Customer Support Service (e-mail: ltppinfo@fhwa.dot.gov).

2.3 Pavement Design Guide

The U.S. National Cooperative Highway Research Program (NCHRP) developed a Mechanistic-Empirical Design Guide for New and Rehabilitated Pavement Structures ("Design Guide") (See http://www.trb.org/mepdg/). This Design Guide and modeling software uses axle load spectra instead of equivalent single axle loads (ESALs) to estimate the effect of traffic on pavements. The axle load spectra consist of axle load distribution factors by vehicle classification. Other inputs such as the hourly distribution of truck traffic are also required.

The Design Guide is structured in a hierarchical manner with three pavement design levels depending on the type of input data available and the design reliability. Level 1 designs require historic axle load spectra data and vehicle classification counts for the project site. Level 2 designs require historic vehicle classification counts for the project site and axle load spectra data for the region. Other levels require only traffic volume and percent trucks.

As the States implement the Design Guide, they are grappling with the cost implications of increased WIM data collection. Pressure for more WIM data collection will probably depend on the sensitivity of the Design Guide to axle load spectra inputs.

2.4 Weight Enforcement

Two systems lead the deployment of mainline WIM for vehicle weight enforcement in North America.

The North American Preclearance and Safety System, or NORPASS, is a partnership of eight U.S. States and one Canadian Province with the trucking industry (see http://www.norpass.net/index.htm). About 60 thousand trucks are registered with them. Another system, called "PrePass®," is a weigh station by-pass services provider (see http://www.prepass.com/). There are twenty-four States and over 240 operational weigh stations that utilize their services. Over 275 thousand trucks are equipped with their transponders.

Both systems have a similar design. When a participating truck approaches a weigh station, its transponder identifies itself to a roadside reader and (at some locations) is weighed by a WIM scale. If weight and credentials are verified, the driver is given a signal to bypass the weigh station. If weight and credentials cannot be verified, a signal instructs the driver to pull into the weigh station for verification. Interoperability is beginning to occur between the truck transponders used for these systems and electronic toll tags used on toll roads.

Distinct from these systems are "virtual weigh stations," which enable mainline WIM systems to be used by enforcement personnel to select trucks for portable static weighing. Mobile vehicle enforcement units connect wirelessly to a WIM system and view real-time truck weight data.

The WIM reading is used for screening vehicles to be stopped downstream and weighed with certified portable scales. Because individual vehicles are being checked, more accuracy is required from the WIM system than for performance monitoring.

In a few States, video imaging is joined with virtual weigh stations to capture identifying information about the trucks. In general, more mainline WIM systems are being used to improve weight enforcement strategies and reduce the need for static weigh stations. An International Conference on Virtual and Remote Weigh Stations was held in February 2004 in Florida (http://www.catss.ucf.edu/Pages/wim_conference.asp).

2.5 Federal WIM Activities

The U.S. Truck Weight Study continues to enlarge its WIM database compiled from the States by the Federal Highway Administration (FHWA). Currently, the database is over 60 gigabytes and growing at almost 10 gigabytes of data per year from about 5000 WIM stations. Soon the States will be able to upload traffic data directly to the database. Summaries of the data are posted on the Internet. The WIM stations have been geo-coded for use in a geographic information system.

The FHWA and the Transportation Research Board (TRB) sponsored the 2004 North American Travel Monitoring Exhibition and Conference (NATMEC), which was held in San Diego, California, in June 2004. The theme was "Obtaining and Using Traffic Monitoring Data for Improving System Performance." Four hundred attendees came from 43 States and seven countries. The exhibitors and conference presentations continued to cover WIM in detail. Instead of a conference report or CD, presentations were posted on the Internet (www.natmec.org).

3. Conclusion

While bridge WIM systems continue to be rare in North America, the use of WIM systems generally continues to grow. The 2001 edition of the Federal Highway Administration's *Traffic Monitoring Guide* (http://www.fhwa.dot.gov/ohim/tmguide/index.htm) has promoted the trend to convert continuous traffic counters to vehicle classification systems and to prefer permanent to portable WIM systems. Then trend toward increased use of WIM for pavement design and weight enforcement is growing.

STATUS AND USE OF WEIGH-IN-MOTION IN AUSTRALIA AND NEW ZEALAND

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Abstract

This paper summarises the status of weigh-in-motion in Australia and New Zealand. In particular the results of a questionnaire (undertaken in November 2004) of Australian and New Zealand Road Transport Agencies is presented detailing the type of weigh-in-motion systems used and the use of the associated data and information. Importantly, the current usage is compared to that of 2002. Additionally the latest end user developments are summarised along with the latest research and development of weighing technology in Australia.

Keywords: WIM, Weigh-in-Motion, questionnaire, application

Résumé

Cet article présente l'état du pesage en marche en Australie et Nouvelle-Zélande. On présente notamment les résultats d'un questionnaire (lancé en novembre 2004) des agences de transport routier australienne et néo-zélandaise sur les types de systèmes de pesage en marche utilisés et les application des données et informations recueillies. La situation est comparée à celle de 2002. En outre les développements les plus récents des utilisateurs finaux et de la recherche sur les technologies du pesage en marche en Australie sont présentés.

Mots-clés: Pesage en Marche, Questionnaire, Applications.

澳洲與紐西蘭動態地磅之使用現況

摘要：

本篇文章針對澳洲與紐西蘭動態地磅 (Weigh-in-Motion, WIM) 之使用現況進行概要介紹。文中特別提出 2004 年 11 月於澳洲與紐西蘭道路運輸局的問卷調查結果，其中詳細敘述所使用之動態地磅系統形式及資料應用的情形，並與 2002 年之使用狀況進行比較。文中並針對動態地磅之最新技術研發情形及澳洲終端使用者概況進行介紹。

關鍵字：動態地磅、問卷、應用

1. Introduction

Australia has been a pioneer in the development and adaptation of Weigh-in-Motion (WIM) systems. The late 1960s and early 1970s saw numerous methods of WIM at highway speeds being investigated. Australia has pioneered the use of a number of different technologies including load cell and strain-gauged mass sensor systems (Samuels 1988 and Peters 1986). Importantly in the last ten years Australian and New Zealand Road Transport Agencies have also investigated, used and adopted non-Australian developed WIM technology.

The purpose of this paper is to present the status of WIM systems and discuss patterns of usage in Australia and New Zealand. In particular a detailed questionnaire was developed and disseminated to Australian and New Zealand Road Transport Agencies with the purpose of determining the current use of WIM technology and the associated data and information. The questionnaire also identified the trend in use over the past 2 years and the end user developments. The paper also makes comment on the latest research and development work being undertaken in Australia with respect to WIM technology.

2. Background

The overwhelming majority high speed WIM system type being used in Australia is CULWAY *(Peter 1986),* CULWAY requires a boxed culvert in which to install the strain-gauged (mass sensor) transducers (Figure 1). Australia's road network has a significant number of boxed culverts that has made CULWAY suitable. In areas where culverts are not present, especially in the urban area, bending plate and capacitive pad WIM systems have been used. In the past few years, as the need for traffic load data in urban areas has become a necessity for infrastructure management, planning and freight movements, a number of IRD Bending Plate, Mikros HSWIM and PAT DAW WIM systems have been installed. Additionally piezo systems and quartz sensor devices have been increasingly adopted.

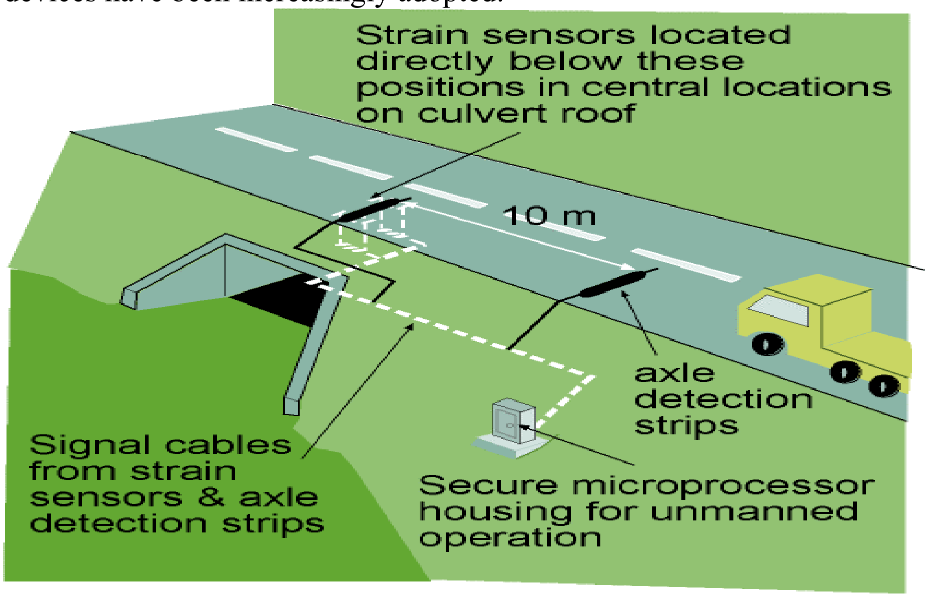

Figure 1 - Layout of the Culway System

3. Survey Details

A questionnaire on WIM was developed by the authors and issued to Australian and New Zealand Road Transport Agencies. The questionnaire is presented in Appendix A. The questionnaire was issued to eight organisations (seven in Australia and one in New Zealand). All eight organisations responded to the questionnaire. Additionally telephone and email contact was made with each of the individual respondees to clarify responses and to identify recent developments. The questionnaire was issued in October 2004 and returned and processed in November 2004.

The questionnaire posed two key questions as follow:

- type of WIM system employed (current number and the change since 2002),
- use of WIM data and information (current usage and 2002 usage).

A number of generic applications and uses of WIM data are presented as follows:

- infrastructure design,
- infrastructure management,
- filtering/screening for enforcement,
- enforcement strategy development,
- direct enforcement (evidentiary level),
- freight/economic planning,
- point of entry/except weighing, and
- safety.

The questionnaire aimed to determine the current number and use of WIM, but also the change over the past 2 years.

4. Results of Survey

4.1 Type of WIM System Employed

The type of WIM system employed in Australia and New Zealand currently and the change over the last 2 years are presented in Table 1.

Weigh in Motion Systems	Total Number in Australasia	Total Change in Australasia since 2002	% Change since 2002
High-Speed Weigh-in-Motion Sites	**108**	+7	**6.5**
High-Speed Weigh-in-Motion Lanes	**235**	+23	**9.8**
Low-Speed Weigh-in-Motion Sites	**11**	+5	**45.5**

Table 1 – Type of WIM System Used

The responses to the questionnaire show that there are currently 108 WIM sites in Australia and New Zealand comprising 235 instrumented lanes. Importantly the total change in High-Speed WIM Sites and associated High-Speed Lanes since 2002 has comprised an increase of 6.5% and 9.8% respectively (Table 1).

The responses also indicated a significant increase in a number of low speed WIM sites. However, the significance of the increase must be considered against the initial low number of such sites (Table 1).

4.2 Application of Weigh-in-Motion Data and Information

The application of WIM data and associated information for Australia and New Zealand is summarised in Table II.

Use/Application of Weigh-in-Motion Data & Information	Total Current Usage (%) in Australasia	Total usage (%) in Australasia 2002	Total change (%) since 2002
Infrastructure Design	24.6	22.2	+2.4
Infrastructure Management	21.6	22.0	-0.4
Filtering/Screening for Enforcement	14.4	10.4	+4.0
Enforcement Strategy Development	15.8	18.7	-2.9
Direct Enforcement (Evidentiary Level)	3.2	1.4	1.8
Freight/Economic Planning	16.2	20.9	-4.7
Point of Entry/Exit Weighing	0	0	0
Safety	4.2	4.4	-0.2
Other (please specify)	0	0	0

Table 2 – Application of WIM Data and Information

Table 2 details the total current usage (%), total usage (%) in 2002, and the change in usage (%) between 2002 and 2004.

The first and most striking feature presented in Table 2 is that the applications of infrastructure design and management collectively comprise 46.8% of total use of WIM data and information. Additionally over the last 2 years there has been a collective increase of 2.4%. It should be noted that the values in Table 2 are calibrated for the number of WIM sites for each of the respondees.

The second observation that can be made from Table 2 is the overall increase in the use of WIM data and information for enforcement related purposes. Filtering and screening of heavy vehicle for enforcement purposes has increased by 4% over the last 2 years and currently comprises 14.4% of WIM data and information use (Table 2). Whilst there has been a decrease by 2.9% in the use of WIM data and information for enforcement strategy development, there has also been an increase of 1.8% in the use of low speed WIM for direct enforcement (evidentiary level) purposes (Table 2). This shows the trend of acceptance and use of WIM technology not simply for enforcement strategy, but for direct use as both screening and direct enforcement purposes. Surprisingly to the authors, Table 2 shows a decrease over the last 2 years by 4.7% in the use of WIM data and information for freight and economic planning purposes. The use of WIM data and information for safety purposes has effectively remained constant at just over 4% over the last 2 years (Table 2).

4.3 End User Developments

In telephone and email contact the respondees identified their developments and activities over the past 2 years. In summary, these were as follows:

- integration of high speed WIM with photographic technology to capture and identify heavy vehicles for the purpose of over mass enforcement,
- undergone major rehabilitation and restoration of WIM sites,
- acquisition and/or use of software package (WIM Net & WIM Link) for the purposes of statistical data analysis,
- development of in-house software for the purposes of managing WIM sites and associated data,
- use of WIM data in the development of the new Austroads Pavement Design Guide (Austroads 2004),
- significant remedial work carried out on pavement surfaces to upgrade the ride-ability and hence improve accuracy of WIM sites,
- completion of a detailed WIM strategy based upon the Austroads documentation *(Austroads 2000)* that recognises the value of more extensive WIM network for transport planning and asset management,
- development of a detailed business case for development of the WIM network.

Some of the more pertinent end user developments are detailed below.

The integration of high speed WIM with photograph technology to capture and identify heavy vehicles is not new to Australia. However, its applicability and widespread use directly with high speed WIM systems, along with its technological improvements has proven to be quite successful. The success has been founded in the ability to produce high resolution images of vehicles identifying the vehicle registration details. Additionally, whilst not of direct enforcement quality, the ability for enforcement officers to collate this information and develop a dossier from which to visit specific transport operators has proved to be invaluable. This has facilitated a process of educating the transport industry in addition to the traditional enforcement initiative.

The new *Austroads Pavement Design Guide to the Structural Design of Road Pavements* (Austroads 2004) has used WIM data extensively for the design traffic section. Importantly traffic load distribution data is required to calculate the design traffic loading. WIM data collected specifically for the project or recently collected for other purposes may be used to estimate traffic design distribution. In the absence of WIM data pavement design guide provides representative results from WIM surveys undertaken throughout Australia. Details of these surveys undertaken and their traffic load distributions derived are presented in Koniditsiotis & Cropley (1998).
The end user developments broadly highlight the ongoing upkeep and maintenance of existing WIM sites and specific development in the area of enforcement. These observations are also highlighted in the summary results presented in Table II.

5. Research and Development

5.1 General

Two major developments have occurred over the last 2 years in the area of Australian developed WIM technology as follows:

- Upgrading of the CULWAY system Logger to CULWAY II,
- Development of Express-Weigh system using Kistler Lineas Quartz sensors, and
- Movement to on-board mass monitoring technology for the purpose of both commercial and regulatory use.

The CULWAY II system provides increase in functionality as identified by users over a number of years. This improvement in functionality allows the ability to measure more lanes, significantly increased storage capacity, lower power consumption, significant increase in the ability to remotely upgrade logger firm-wear and interrogate system.

The Express-Weigh system was developed part in recognition of the need for an Australian based high speed WIM that could be used in locations in which a culvert (ie. for a CULWAY for CULWAY II) was not available. The major development in the Express-Weigh system is the integration of the Kistler Lineas Quartz sensor into the existing logger.

5.2 Intelligent Access Program

Access to the Australian road network is at present by general access and restricted access. Through the use of technology a third generation of access, *Intelligent Access*, is being introduced. The Intelligent Access Program (IAP) provides an innovative solution for governments in Australia to better manage the road network asset. The objective of IAP is the implementation of a national system that will remotely monitor freight vehicles to ensure vehicles are complying with their agreed operating conditions, that is ensuring they operate how, where and when they should.

Private sector service providers would provide the services to underpin the IAP. These service providers would ideally combine IAP services (ie. compliance monitoring) with commercial services, some of which are currently available. There will be a requirement for a certification and auditing regime established to ensure that private sector service providers meet the requirements under IAP. Transport operators would be prepared to use IAP on a fee-for-service basis to gain improved access to the road network (Figure 2). The IAP will be a pre-requisite to entering schemes that offer benefits to the transport operator and under IAP governments will be informed of any transport operator non-compliance by service providers.

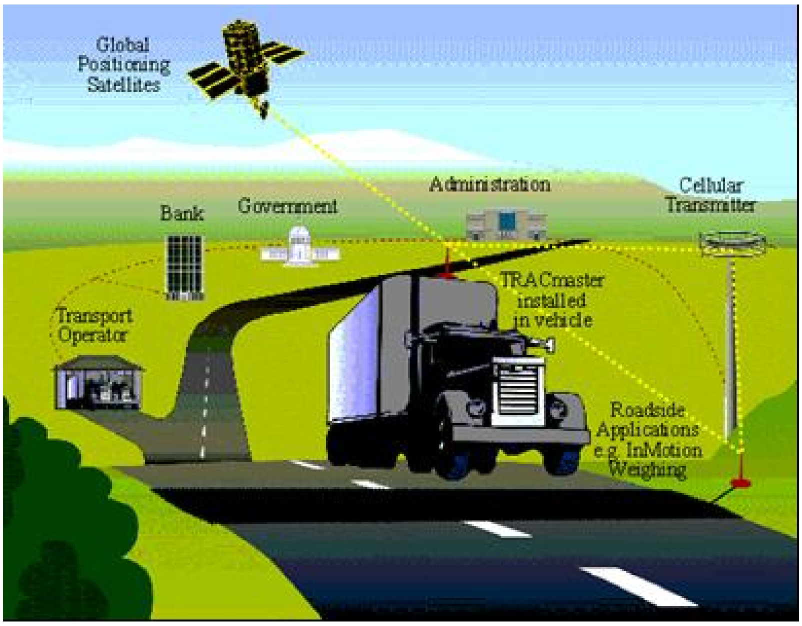

Figure 2 - Schematic of the Intelligent Access Program (IAP)

The IAP has also considered the use of heavy vehicle on-board mass monitoring as a regulatory (in addition to commercial) tool. The preliminary assessment identified the need to further technical investigation on accuracy and tamper evidence determination and also to a lesser degree certain cost implications. On-board mass monitoring for heavy vehicles has been used for commercial purposes by a number of industry operators. The move into the regulatory sphere is new and poses certain significant benefits. From an IAP perspective the preliminary benefits are improved access to the road network based on an individual vehicle by vehicle knowledge of the actual mass. This also offers the potential for future applications exploring new significant policy considerations.

An important challenge which needs to be investigated by both industry and governments in the future will be the synergy and interconnectivity by both on-board and on-road (ie WIM) technology. Clearly this provides an opportunity to manage a number of issues including that of evidentiary level data collection. Issues of interconnectivity and interoperability can be well managed through existing standards or standards developed specifically for the purpose of communicating from WIM to the vehicle. The more fundamental issue that needs exploration is developing and understanding the underlying policy drivers rather than the technical drivers. This is an area of investigation which is not only part of the Australian sphere but also applicable across a number of countries.

6. Conclusion

The use of WIM technology in Australia and New Zealand is active. Over the past 2 years there has been an overall steady increase in the number of systems and instrumented lanes of just under 10%. Importantly, it is recognised that the use of the WIM data and information is predominantly in the area of infrastructure design and management. The use of WIM data and information for enforcement purposes has increased over the last 2 years, especially in the area of filtering for enforcement and direct (evidentiary level) enforcement purposes. Whilst new WIM technology has progressed in Australia in the form of improved loggers and the use of Quartz sensors, over this period, it appears that road transport agencies have consolidated their use of WIM systems (maintenance and upkeep of systems) and the integration of WIM *per se* with other systems to provide increased functionality. In particular, in the use of camera based technology for the identification and capture of heavy vehicle images for the purposes of enforcement and compliance with relevant regulations. Additionally, the IAP is considering the use of heavy vehicle on-board mass monitoring in addition to WIM.

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Appendix A

Questionnaire on Weigh-In-Motion (WIM).

Name: ______________________________________

Organisation: ______________________________________

Q1. Type of WIM system employed:

	Weigh in Motion System	Current Number	Change since 2002 (e.g. no change to +2 or +3 etc)
1	High-Speed Weigh-in-Motion Sites		
2	High-Speed Weigh-in-Motion Lanes		
3	Low-Speed Weigh-in-Motion Sites		

Q2. Use of WIM data & information:

	Use/Application of Weigh-in-Motion Data & Information	Current Usage* (%)	2002 Usage* (%)
1	Infrastructure Design		
2	Infrastructure Management		
3	Filtering/Screening for Enforcement		
4	Enforcement Strategy Development		
5	Direct Enforcement (Evidentiary Level)		
6	Freight/Economic Planning		
7	Point of Entry/Exit Weighing		
8	Safety		
9	Other (please specify) ---		

Note: The usage in percent (%) should for each column sum to 100%.

It would be appreciated if your response to this questionnaire is received by 12 November 2004.

Thank you for your time and effort in completing this questionnaire. Please e-mail your response to Craig D'Souza (cdsouza@ntc.gov.au) or fax to Craig D'Souza on (03) 9642 8922.

SESSION 1 :

WIM TECHNOLOGIES AND TESTING

Chairperson: Barbara Ostrom
Co-chair: Raid Karoumi

MS-WIM ARRAYS DESIGN OPTIMISATION



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Abstract

Accurate static weight estimates are needed to meet overloading automatic enforcement purposes. Multiple-Sensor Weigh-In-Motion (MS-WIM) is one of the most suitable way to obtain these precise data. Accuracy of the estimation mainly depends on the individual sensor measurement accuracy, estimation algorithm performance, and MS-WIM array suitability. Thus, this paper proposes a method to optimise MS-WIM array design (number of sensors, sensors spacings, sensors location). Those parameters are optimised using truck/road dynamic interaction simulation software. This optimisation method was applied to a new MS-WIM test site to be designed in Eastern France on National Road 4.

Keywords: MS-WIM, Array, Design, Sensor Spacing, Sensor Location, Optimisation.

Résumé

Une estimation précise des poids statique est nécessaire pour remplir les exigences du contrôle sanction automatique des surcharges. Le pesage en marche multicapteur (MS-WIM) est un des outils appropriés pour obtenir ces données. La précision de l'estimation dépend principalement de la précision individuelle des capteurs, des performances de l'algorithme, et du dimensionnement de la grille de capteurs. Ainsi, cet article propose une méthode pour optimiser les grilles multicapteur (nombre de capteurs, distance intercapteur, position des capteurs). Ces paramètres sont optimisés à l'aide d'un logiciel de simulation des interactions dynamiques poids lourd/infrastructure. Cette méthode d'optimisation est appliquée au nouveau site MS-WIM qui sera implanté dans l'Est de la France sur la Route Nationale 4.

Mots-clés: Pesage en Marche Multicapteur, Grille, Dimensionnement, Distance Intercapteur, Position des Capteurs, Optimisation.

多重感測器－動態地磅之最佳化的排列設計

摘要：

爲了要能執行全自動超載執法取締，精準的預估車輛靜態荷重是必要的。多重感測器之動態地磅 (Multiple-Sensor WIM) 爲能獲取準確資料的方法之一。準確的估算主要依靠個別偵測器精準的量測、運算方法之績效、以及多重感測器動態地磅排列設置的合理性。因此本篇文章之目的在於闡述多感測器動態地磅排列設計的最佳化方法(如感測器的數量、感測器間距、設置位置)。以卡車與道路間的動態交互影響模擬軟體作爲參數最佳化之工具。而此套多重感測器最佳化之設計方法已用於法國東部的#4 國際道路上。

關鍵字：多感測器動態地磅、排列、設計、感測器間距、感測器位置、最佳化

1. Introduction

Multiple-Sensor Weigh-In-Motion (MS-WIM) is one of the most suitable way to accurately estimate static axle loads using WIM at traffic speed. Research works were carried out since 1989 on MS-WIM (Glover and Newton, 1991). Each axle applies a vertical force varying in time on the pavement. This force will be designated as the impact force hereafter. Repeating the measurement of the impact force along the pavement with an array of strip sensors allows to sample this force. Appropriated algorithms based on different theoretical approaches were previously developed to get rid of the pavement-vehicle dynamic interaction effects and estimate the static weight (WAVE, 2002). Those algorithms, applied to MS-WIM data, lead to an accurate estimation of axle static weight, even if this accuracy is not yet sufficient for enforcement purposes.

There are three complementary possibilities for accuracy improvement: sensor's intrinsic accuracy improvement, static weight estimation algorithms improvement, and array design optimisation. The two first fields were investigated (Labry et al., 2005; Dolcemascolo et al., 2002), although some further researches are still necessary.

This paper will focus on array design optimisation. Many parameters as sensor number, sensor spacing, total length and location of the array, sensors quality (noise), road characteristics (evenness, deflection, slope,…), define a MS-WIM array. All of them could affect the MS-WIM array efficiency. However, this paper will particularly investigate sensor spacing, sensor number, and array location.

Some previous theoretical researches were carried out to optimise the sensor spacing (Cebon and Winkler, 1991; Cebon, 1999; Stergioulas et al., 1998) with respect to the trucks dynamics. Experimental approaches taking into account spatial repeatability influence were also proposed (Dolcemascolo and Jacob, 1998; Labry et al., 2004). This paper proposes to extend this last method to the influence of the sensor number and sensor location.

2. Simulated Data

It was decided to choose a simulation approach to provide impact forces data considering it is a cheap and comfortable 'sensor noise free' solution to control trucks parameters variations. The software PROSPER (PROgram of SPEcification and Research components), developed by the French company SERA-CD, was chosen to simulate the dynamic behaviour and the interaction between trucks and road. This software is based on a 3D computation engine, with 29 Degrees of Freedom, coupled and non linear with 600 variables. Some parts of the software were validated by the DGA-ETAS (French Ministry of Defence) with a real truck (Delanne et al., 2003). The truck model is built with pre-designed elements stored in user's libraries, such as loads, axle spacing, number of axles, etc... PROSPER takes into account the ground inputs (2D or 3D road profile). Simulation options allow to assign a trajectory, speed, and all driving parameters, a detailed truck description (mechanical truck characteristics, axle static load, load distribution in the truck, speed, etc…) and also some environmental characteristics (road profile, pavement slope, skid resistance,…). The output parameter we were interested in is the resulting impact force for each axle.

The two simulated trucks were chosen according to French traffic path as found in (Jacob and Labry, 2002). A 5-axles trucks with 2 axles for the tractor and a group of 3 axles for the semi-trailer, and a 2-axles rigid truck were selected to represent the French traffic distribution.

PROSPER 2-dimension road profile input for impact forces simulation was measured on national road 4, where it is aimed to install a MS-WIM array in 2005 (Stanczyk et al., 2005). It was characterised with the Longitudinal Profile Analyser (APL) and obtained the following ratings: 8.6 - 9 - 8 respectively for short, medium, and long wavelength, the International Roughness Index (IRI) being 1.17m/km. This site was found to be a good WIM site (class II) according to the COST323 European Specifications of WIM (COST323, 2002).

Load, height of vehicle gravity centre, distance between axles, speed and suspension deflection factor were varying according to the simulation program described in (Labry et al., 2004). Complete description of PROSPER software, including model parameters and suspension description is available in (Schaefer, 2002).

3. Optimised MS-WIM Arrays

The calculated impact forces are sampled along the road profile such as they would be measured by a MS-WIM array of sensors.

First, as national road 4 is a good site according to COST323 specification (class II), it was decided to evaluate the influence of the sensors location along the road profile. An optimised location was calculated and compared with the location that would have been chosen for practical concerns.

Then different sensors spacings were calculated according to two described methods, with 4 to 16 sensors arrays. In this study, only uniformly spaced sensors arrays were considered.

3.1 Sensor Location Optimisation

The APL measured the altimetry under each wheel over 1km in the area chosen for the MS-WIM array location. Abscissa x=0m was defined as the best location for practical concerns (shortest distance to the telephone or electrical network, appropriate distance to the static weighing area, etc...). The variations of the road profile altimetry define its quality with respect to the impact forces. Thus, the area within the profile where the standard deviation of the road profile signal was minimum was identified (Figure 1).

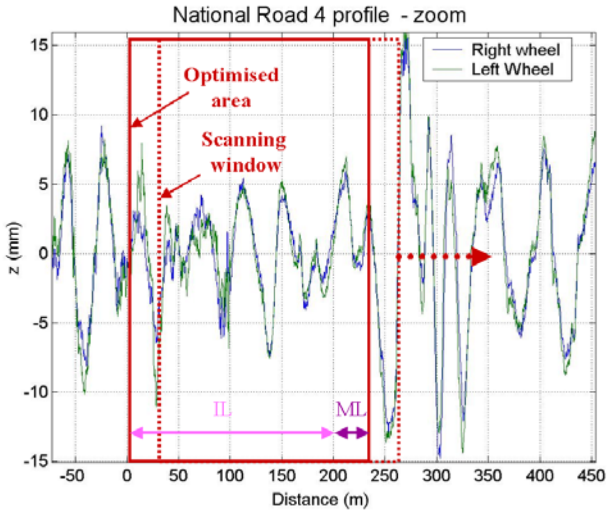

Figure 1 - Scanning Window on National Road 4 Road Profile

A window with a width *w* was defined to scan the profile signal. The width *w* takes into account the MS-WIM maximum array length (ML), estimated around 40m and also the influence length (IL). The influence length is the distance along which the road profile characteristics influence the impact forces on the following area, and it has to be estimated. It is usually considered that the effect of a perturbation on the impact force is damped within 5 to 10 wavelengths.

In the frame of DIVINE OECD project (Jacob and Dolcemascolo, 1997), three main frequency ranges were considered as representative of the trucks dynamics : 1,5Hz to 2,5Hz (body motion : pitching, bouncing, rolling and yawing), 3,5Hz to 5Hz (suspensions vibration, body vibration first harmonic) and 10Hz to 15Hz (unsprung mass vibration). The maximum mean speed was considered as 30m/s, which, combined with the lowest eigenfrequency (1.5Hz) leads to maximum wavelength of 20m. Thus, the influence length was defined as 200m. Figure 2 shows the standard deviation results with respect to the first sensor location.

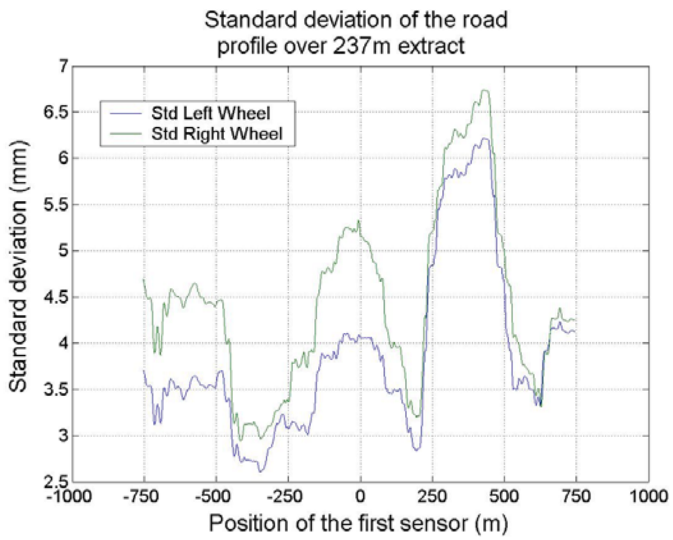

Figure 2 - Standard deviation of the road profile (237m window)

Three almost equivalent minima are observed for each wheel. Because the results of this study had operational applications on national road 4 MS-WIM array, the closest minima (x=195m) from the initially planned location (x=0m) was chosen. According to this figure, standard deviation are quite high for the initially planned location, above all for the right wheel. This will allow a comparison of the two locations.

3.2 Sensor Spacing Optimisation

Cebon's formula (Cebon and Winkler, 1991; Cebon, 1999) gives an optimised sensor spacing for a small number of sensors, using a sinusoidal impact force model and a random noise. Theory was extended by Stergioulas et al. (1999) to a larger number of sensors, using a two sines impact force model, and led to Stergioulas' formula, which will be named Method A hereafter.

An alternative method was proposed and consists in using simulated impact forces to calculate the optimal sensor spacing which minimises the static weight estimation error, and which, as a result, includes trucks dynamics and road profile influence. This method will be named Method B hereafter.

Cebon's and Stergioulas' Formulas

Theoretical studies on MS-WIM using a 'SAve' (Simple AVErage) method were carried out by (Cebon and Winkler 1991, Cebon 1999). An optimal design of a n-sensors (uniformly spaced) MS-WIM array was defined by modelling the impact force by a single sine and random noise. A formula was proposed to calculate the optimum spacing d of n sensors, as a function of n, of the mean traffic velocity V (m/s) and of the mean bounce motion frequency of the trucks f (Hz):

$$d = \frac{2.(n-1).V}{f.n^2} \tag{1}$$

This theory determines the envelope error of the MS-WIM estimation according to the sensor spacing. Formula (1) ensures the calculated spacing will be located on the smooth part of the envelope error. Extension of this theory to two sine waves model led to formula (2) taking into account both bouncing (f1) and axle hop (f2) frequencies (Stergioulas et al., 1999):

$$d_2 = \frac{V}{2.n}\left(\frac{1}{f_1} + \frac{n-1}{f_2}\right) \tag{2}$$

Proposed Array Design Optimisation Method

The advantage of the proposed method is the use of simulated impact forces (see section 2) calculated with both trucks dynamics and road profile (Labry et al., 2004). The part related to the trucks dynamics varies from one vehicle to the other, but the part related to road profile shows relevant similarities for all the trucks. This spatial repeatability phenomenon was shown in the OECD/DIVINE project (Jacob and Dolcemascolo, 1998).

Impact forces were averaged, and the sensor spacing which minimizes the mean error and standard deviation of the static weight estimator was searched. To find this optimum spacing, the impact factors (relative error between the dynamic force and the static load of the axle) were averaged for all simulated trucks according to three different criteria: gross vehicle weight GVW, single axles SA, and group of axles GoA.

The averaged impact factor is sampled into n equally spaced points (n sensors, $4 \le n \le 16$). Sensors spacing was varying in the range 0.7-5 m (with 10^{-3} m steps). The impact factor values for each spacing were averaged, and, in order to evaluate the performance of the array, the mean error m and the standard deviation s of the error were calculated. Then the static load estimator, i.e. the sensor spacing, was chosen to minimize m^2+s^2. Figure 3 shows an optimisation example and Table 1 presents the summarised results for each method.

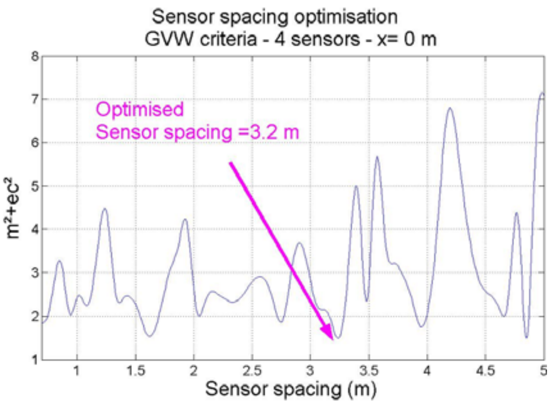

Figure 3 - Sensor Spacing Optimisation

Table 1 - Calculated sensors spacings

Sensor Nb	**Sensor spacing (m)**		
	Method A	Method B x=0m	Method B x=195m
4	2.37	3.2	2.37
5	2.12	2.76	2.42
6	1.95	2.23	2.05
8	1.74	2.75	2.25
10	1.62	2.76	2.25
13	1.50	2.75	2.54
16	1.43	2.41	2.55

4. Static Weight Estimation Algorithms

Two MS-WIM algorithms as detailed hereafter were applied to these raw data, resulting from trucks simulation and sampled according to the designed MS-WIM arrays.

No random noise was added to simulate the real sensor behaviour, because it was not aimed to compare the static weight estimation algorithms. As this study will compare several array designs, the influence of a random noise was considered as disadvantaging our analysis.

First used algorithm is the simple average estimation. Assuming that the spatial mean of the axle impact forces is equal to the static axle load, leads to average these dynamic loads, measured by a set of uniformly spaced sensors of a MS-WIM array. This estimation by a "Simple Average" is denoted here as 'SAve' method.

The Signal Reconstruction and Kalman Filtering Method (SR) was developed in the LCPC (Sainte-Marie et al, 1998) in the frame of WAVE European project (WAVE, 2001). This deterministic approach consists of a reconstruction of the continuous dynamic axle impact force signal, using the sample of impact forces measured by each sensor of the MS-WIM array. Then, the static axle load is estimated by the mean of the reconstructed signal, on a given road length

(L). L depends on bouncing and rolling frequencies, which are estimated by an extended Kalman filtering procedure.

5. Accuracy results

Accuracy of the static weight estimation by the above presented algorithms is evaluated by the delta min value (dmin), according to the European WIM Specifications (COST323, 2002). dmin is the half-width of the confidence interval for a required minimum level of confidence defined by the specifications. It is calculated for four criteria: Gross Vehicle Weight (GVW), Group of Axles (GoA), Single Axles (SA), and Axles of a Group (AoG).

5.1 First sensor location's influence

Figures 4 and 5 show the compared delta min values (for each criteria) for two sensor's location influence, for increasing number of sensors, and resp. for arrays designed with Method A and SAve static weight estimation algorithm, and for arrays designed with Method B and SR algorithm. Results with SAve algorithm and Method B, as well as results with SR algorithm and Method A are not presented here because they did not provide any additional information. Actually, the static weight estimation algorithm, compared to the array design method, seems to be a preponderant parameter influencing the accuracy.

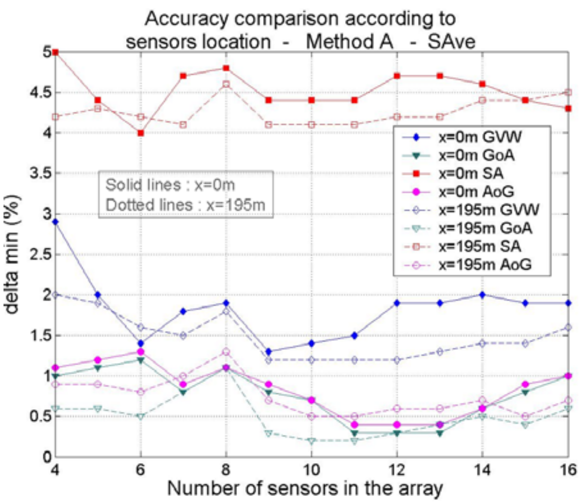

Figure 4 - Influence of Sensors Location Method A - SAve Estimation

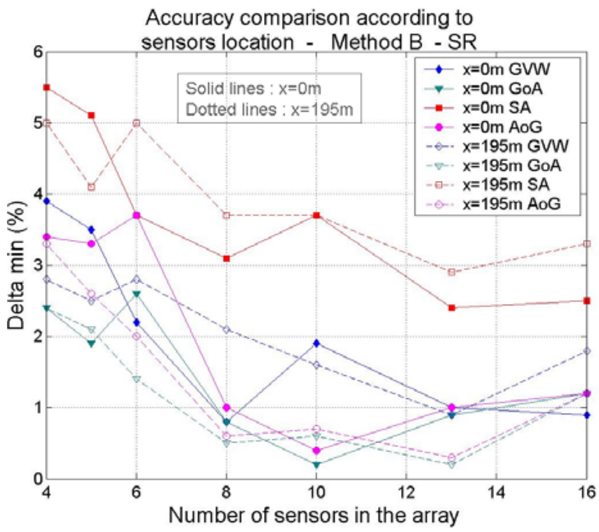

Figure 5 - Influence of Sensors Location Method B - SR Estimation

Sensor's location optimisation leads to a slight accuracy improvement with SAve method. While averaging the impact force samples, this method get rid of the impact force variation amplitude influence, when the sensors array is appropriated. This phenomenon can explain the limited influence of the sensors location.

As expected, comparison for SR algorithm does not lead to any significant accuracy improvement. SR theory stands its independence regarding to the array design. This method allows indeed to reconstruct the impact force, whatever the variation amplitude. MS-WIM array response is then supposed to be independent with respect to the road profile phase. It is not useful to look for a 'best location' to install sensors. This conclusion might not be verified in case of road profiles with bumps, but it is already recommended in COST 323 specification that WIM sensors must be installed far away from any major bump. Thus, hereafter, arrays with first sensor's location x=0m will be considered, as it was chosen as the best choice for practical concerns on RN4.

5.2 Sensor Spacing Optimisation Method's Influence

Figure 6 shows the delta min values (for each criteria), for SAve static weight estimation algorithm, in order to compare the accuracy according to the array design method.

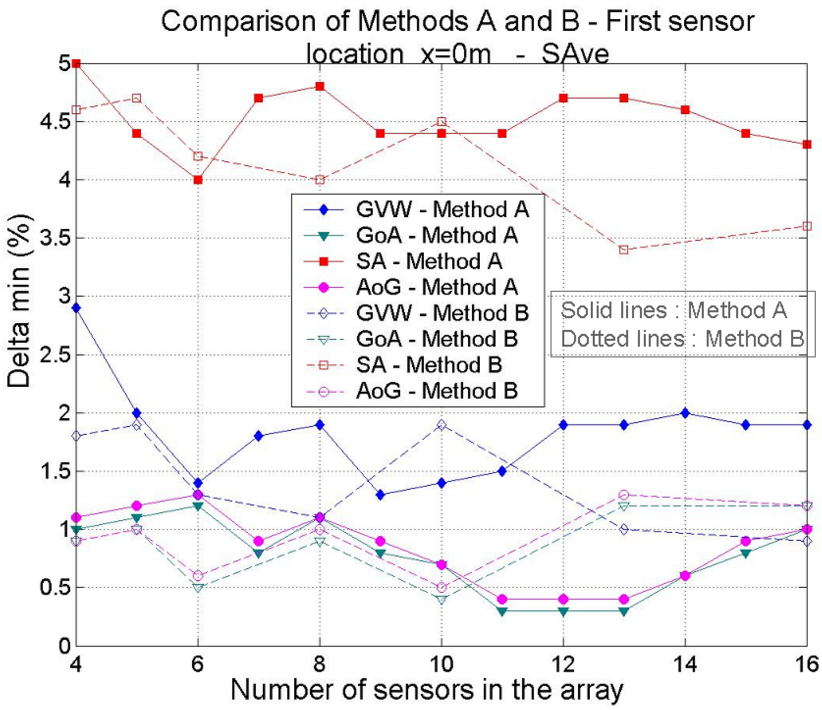

Figure 6 - Method A and Method B Comparison - First Sensor x=0m - SAve Estimation

Single Axles weight, and, by extension, Gross Weight estimations, are slightly improved (1%) with the proposed method (Method B), particularly for number of sensors over 8. Delta min value with Method B seems slowly decreasing with the number of sensors, except for the 10 sensors array. No reason could be found to explain the particular behaviour of this array. Axles of group and group of axles accuracy seems independent with respect to the design method. Differences observed are not considered as significant.

Fgiure 7 proposes the same comparison with SR static weight estimation algorithm. Differences between the two methods are less significant, except for large number of sensors (over 8) and again, Single Axles and Gross Weight criteria, for which the accuracy improvement with Method B is respectively 0.5% and 1%. Again, SR algorithm already proved by theory and previous experimentation to be quite independent regarding to the array design.

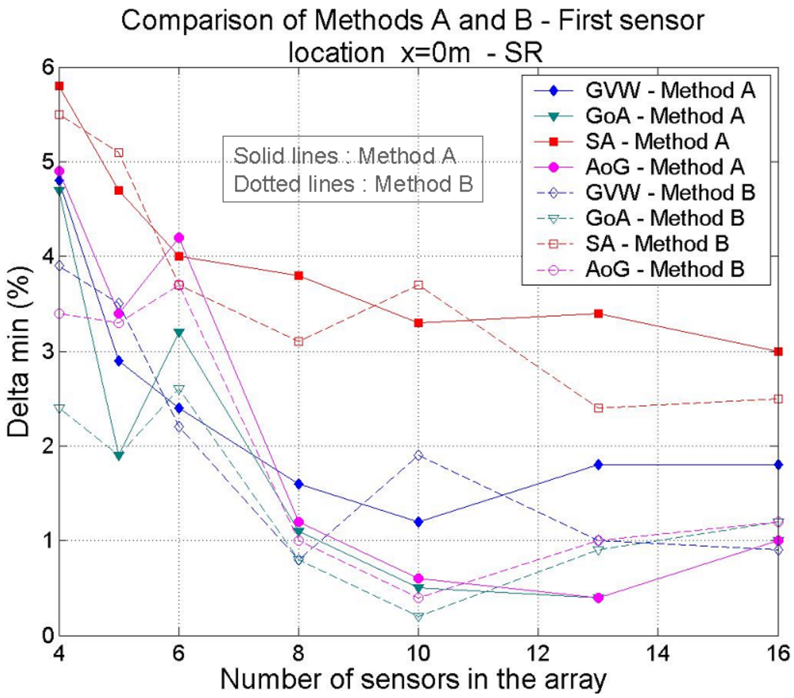

Figure 7 - Method A and Method B Comparison - First Sensor x=0m - SR Estimation

5.3 Static Weight Estimation Algorithms Comparison

Figure 8 shows static weight estimation algorithms comparison with Method B for the array design. Same comparison with Method A is not presented here because results had a similar behaviour. For sensor number up to 5, SAve method provides the best accuracy whatever the observed criteria. For sensor number from 5 to 8, SR estimation reaches better accuracy for Single Axle criteria only. For arrays with more than 8 sensors, accuracy results are equivalent for Gross Weight, Axles of Group and Group of Axles, but approximately 1% improvement is observed on Single Axles criteria.

As it was already noticed from the previous figures, SR estimation is very dependent on the number of sensors composing the array. From these simulations, the best compromise between the cost (linked to the number of sensors) and the accuracy is observed with the 8 sensors array. No significant accuracy improvement is shown for arrays with larger number of sensors. From Figure 8 and the previous figures, it is shown that SAve is rather independent with respect to the number of sensors over 4 or 5.

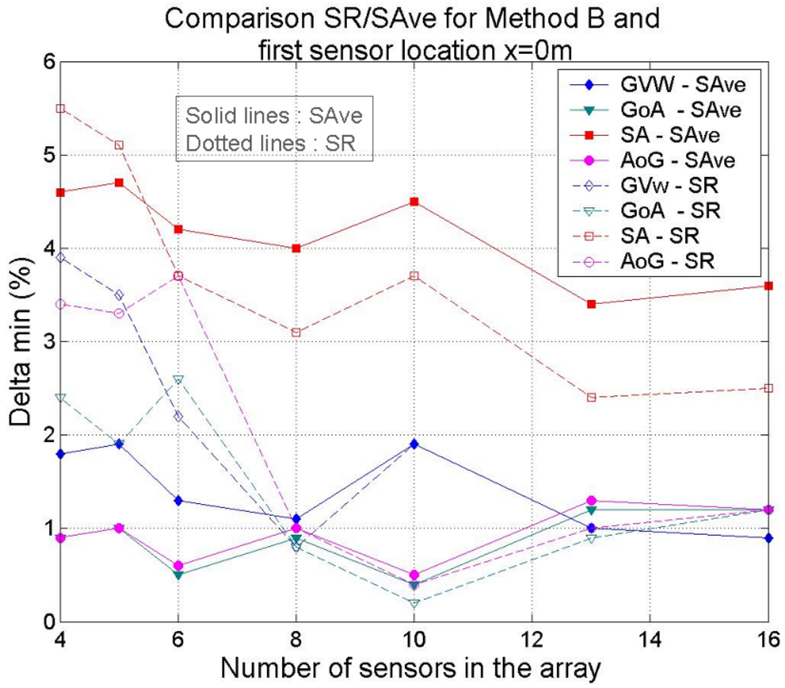

Figure 8 - SAve and SR Estimation Comparison – Method B – First Sensor x=0m

6. Conclusions

The proposed method for MS-WIM arrays design, taking into account spatial repeatability, was tested for various numbers of sensors and two static weight estimation algorithms. The method was compared to Stergioulas' method.

No important influence was noticed with respect to the MS-WIM array along the road profile, particularly for SR algorithm, and the static weight estimation accuracy was proved to be rather independent on the road profile signal phase. Obviously, this conclusion would probably not be verified if a major bump was located within the influence or array area.

SAve static weight estimation algorithm was shown rather independent on the number of sensors (from 4 to 16), but sensitive to the array design. As it was shown in previous studies (Labry et al., 2004) the influence of the array design can have an important influence in case of a badly designed array, or in particular configurations. Accuracy differences here are not so important because the compared arrays were both well designed. However, proposed sensor spacing optimisation allowed to reach more accurate estimation of Gross and Single Axles static weight. Arrays composed of 4 or 5 sensors were shown to reach equivalent accuracy than larger number of sensors.

SR algorithm, as expected from the theory, did not show any important sensitivity regarding to the array design. However, the gain of this complex algorithm compared to the simple averaging method is hidden for sensors number less than 8. Advantage of SR is particularly shown for Single Axles estimation and sensor number over 8. Number of sensor within the array was proved from these simulations to be optimised when equal to 8.

This study led to recommend on RN4 future MS-WIM test site a multiple-sensor array with spacing calculated according Method B, whatever the sensor location. 16 sensors will compose the array, but particular attention will be paid to the confirmation of an existing optimised sensor number. SR and SAve method will still be used and compared, and influence of real and noisy data will be studied.

Obviously, authors are conscious that these conclusions are obtained from simulations, which are never exactly representing in situ reality. The truck sample was not fully representative of traffic, and no noise was taken into account. Validation of some parts of these results are planned with real measurements on national road 4 test site. But influence of sensor spacing or noise level won't be allowed. Thus, simulation remains a very useful tool for WIM applications. Further research will also be carried out in order to correlate this experimental approach with theoretical considerations.

Acknowledgement
This research received financial support from the Ground Transportation Division (DTT) from the French Ministry of Transport.

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THE USE OF FUNCTIONAL NETWORKS TO OPTIMISE THE ACCURACY OF MULTIPLE–SENSOR WEIGH-IN-MOTION SYSTEMS

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Abstract
The accuracy of multiple-sensor weigh-in-motion systems is severely limited by the magnitude of noise and vehicle dynamics. Neural networks have been recently tested for removing noise and identifying patterns of spatial repeatability. However, this technique might require an impractical number of statically weighed trucks for calibration/training. This paper proposes the use of functional networks as an alternative to neural networks. Unlike neural networks, which are “black boxes”, functional networks arise directly from the equations governing the weigh-in-motion problem. The functional network equations are taken from given families of functions. The function parameters are calculated during the learning process and adjustment of scalar 'weights' is not necessary. Vehicle simulations are used to show the potential of this approach.

Keywords: WIM, MS-WIM, Weigh-in-Motion, Functional Networks, Accuracy, Neural Networks, Multiple Sensor.

Résumé
La précision des systèmes de pesage en marche multicapteurs est strictement limitée par l’amplitude du bruit es capteurs et de la dynamique des véhicules. Les réseau de neurones ont été récemment essayés pour éliminer le bruit et identifier l’effet de la répétabilité spatiale. Cependant cette technique peut nécessiter un nombre inaccessible de poids lourds pesés en statique pour l’étalonnage/apprentissage. Cet article propose d’utiliser des réseaux de fonctions plutôt que de neurones. Contrairement aux réseaux de neurones qui sont des « boîtes noires », les réseaux de fonctions découlent directement des équations qui gouvernent le pesage en marche. Les équations du réseau de fonctions sont issues de familles de fonctions. Les paramètres des fonctions son calculés pendant la phase d’apprentissage et l’ajustement de coefficients de pondération n’est pas nécessaire. Des simulations de véhicules sont utilisées pour montrer le potentiel de cette approche.

Mots-clés: Pesage en Marche, Réseaux de Fonctions, Précision, Réseaux de Neurones, Multicapteur.

使用函數路網運算以最佳化多重感測器動態地磅之準確性

摘要：
多重感測器動態地磅之準確性主要受限於量測資料之雜訊以及車輛震動嚴重程度，類神經路網近來已嘗試用於雜訊移除和辨認空間特性之重複性。但是該技術需要大量之靜態卡車重量以爲校估或訓練。本篇文章之目的即在利用”函數路網” (functional network) 取代類神經網路。其最大不同處即是函數路網採用設計動態地磅之控制方程式，而不以類神經網路之”黑盒子”作業系統。函數路網之方程式取自先前所給之家族方程式。方程式的參數由學習過程中計算而得，載重量大小之調整並非必須。本方法之未來潛力可由車輛模擬之成果看出。

關鍵字：動態地磅、多感測器動態地磅、功用、路網、準確性、類神經路網、多感測器

1. Introduction

The consistent development of Weigh-in-Motion (WIM) technologies in recent years has resulted in a significant improvement in the durability and accuracy of estimations of static vehicle weights. However, the current accuracy of single and two-sensor WIM systems is still not considered to be sufficient for enforcement of the legal limits on axle and gross vehicle weights. Multiple-Sensor WIM (MS-WIM) arrays are seen by many as having the best potential to achieve the high levels of accuracy necessary for enforcement, i.e., class A(5), according to the COST 323 specification (1999).

A number of techniques have been used to process the output from MS-WIM systems into axle and gross vehicle weights. It has been shown that algorithms such as the Maximum Likelihood estimator or the use of Signal Reconstruction and Kalman filtering method have produced good theoretical results. However, in practice, their accuracy was no better than that obtained from simple average-based calibration algorithms due to their sensitivity to high levels of noise (Dolcemascolo, 1999).

The application of artificial Neural Networks (NN's) to the MS-WIM problem was first published by Black et al. in 2002. NN's consist of a large number of weighted connections among a number of layers of neurons. These weighted connections are calculated using a scalar activation function, usually the sigmoidal (S-shaped) function. The connection weights are adjusted until a best fit is found for the given signal. While showing considerable potential, especially at high noise levels (González et al., 2003), the NN approach is limited by the use of a standard input processing function which bears no relationship to the physical processes involved. This results in a less realistic representation of the process and an unnecessary separation of the physical process from the numerical model.

Castillo et al (1998) introduce Functional Networks (FN's) as an alternative to and more general form of NN's. FN's can identify and make use of knowledge of the physical and engineering properties of the underlying process being modelled. This is in contrast to NN's, which are "black boxes" and do not take into account the underlying structure of the process. This paper analyses the performance of a FN algorithm when applied to the outputs from a MS-WIM system and it compares the results to NN's and average-based algorithms.

2. Vertical Forces applied to a Rough Surface by a Mass in Motion

Prior to the derivation of the FN's topology, it is necessary to have an understanding of the MS-WIM problem. Measurements from MS-WIM systems depend on the road profile, noise and vehicle velocity & dynamic properties. Noise is a random error component, velocity can be accurately determined from road sensors and vehicle dynamics are governed by two main movements: a body oscillation with a frequency between 1.5 Hz and 4.5 Hz, related to the stiffness of suspensions and sprung mass (vehicle body), and an axle oscillation with a higher frequency (8 to 15 Hz), mainly related to the unsprung mass (wheels and axles) and tyre stiffness. As the road unevenness increases, WIM measurements are more influenced by a phenomenon known as spatial repeatability in dynamic impact loads (O'Connor et al., 2000), defined as localised patterns in the loads associated with pavement location. Spatial repeatability makes it difficult to estimate the static axle weight accurately. FN's are expected to be able to identify and remove if desired, these underlying patterns of spatially repeatable components of dynamic impact force.

For this preliminary study, a vehicle axle was idealised as a simple sprung mass with one single degree of freedom (one single frequency representing the fundamental mode of vibration of the suspension/tyre axle system). Other frequency components and redistribution of weight between axles were neglected.

2.1 Vehicle-Pavement Dynamic Model

The vehicle parameters are the mass *M*, spring constant *K*, damping coefficient *C* and constant velocity *V* as illustrated in Figure 1. The height of road irregularities is defined by $r = r(t)$.

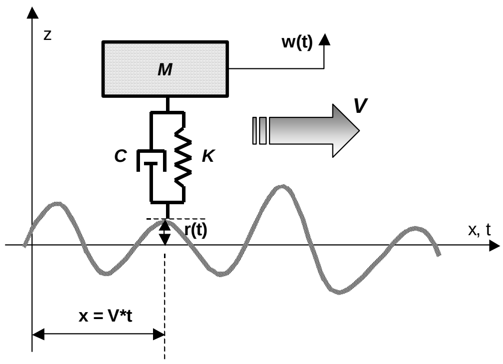

Figure 1 – Sprung Mass Model Moving on a Road Surface

By applying Newton's 2nd law to the system of forces acting on the mass *M* of Figure 1, it is possible to derive the following equation of motion:

$$M\frac{d^2w(t)}{dt^2}+C\left(\frac{dw(t)}{dt}-\frac{dr(t)}{dt}\right)+K(w(t)-r(t))=Mg \tag{1}$$

where *g* is the acceleration due to gravity and *w(t)* is the position of the sprung mass at time *t*. If $y(t) = w(t) - r(t)$, then Equation(1) becomes:

$$M\frac{d^2y(t)}{dt^2}+C\frac{dy(t)}{dt}+Ky(t)=M(g-\frac{d^2r(t)}{dt^2}) \tag{2}$$

where *y(t)* is the displacement of the axle relative to the level of the road profile or compression of the spring in Figure 1.

The vibration of the vehicle can be determined readily once the response $y(t)$ is solved for the given forcing function $M(g-\frac{d^2r(t)}{dt^2})$. The applied dynamic force at instant t or WIM measurement (ignoring noise) at location x ($x = V*t$) is described by Equation (3).

$$WIM_{x=t*V} = C\frac{dy(t)}{dt} + Ky(t) = M(g-\frac{d^2r}{dt^2}-\frac{d^2y}{dt^2}) \tag{3}$$

2.2 Definition of the Road Profile

The magnitude of the vehicle response strongly depends on its velocity, V, and on the unevenness of the road profile, $r(t)$. In this paper, the road profile is assumed to be a random process described by a power spectral density function, $S(\omega)$. The frequency axis of the function $S(\omega)$ is divided into N equal intervals with spectral density values $S(\omega_1)$, $S(\omega_2)$,…, $S(\omega_N)$ corresponding to spatial circular frequencies ω_1, ω_2,…,ω_N. Then, Equation (4) is used to generate sample road profiles.

$$r(x) = \sum_{i=1}^{N}\sqrt{4S(\omega_i)\Delta\omega}\cos(\omega_i x - \theta_i) \tag{4}$$

where

- N : Number of discrete frequencies in the range $(\omega_{min}, \omega_{max})$ where ω_{min} *and* ω_{max} are the lower and upper bounds respectively of the interval in which the power spectral density function is defined,
- $\Delta\omega$: Frequency increment, $\Delta\omega = (\omega_{max}-\omega_{min})/N$,
- $S(\omega_i)$: Power spectral density function,
- ω_i : Spatial circular frequency, $\omega_i = \omega_{min} + \Delta\omega*(i-1)$,
- θ_i : Independent random variable uniformly distributed in the range from 0 to 2π.

A different array of random numbers θ_i will generate different profiles within the same road class. Attending to the classification of road roughness given by the ISO (**I**nternational **S**tandards **O**rganisation) specifications, the power spectral density function of the spatial natural frequency for highway surface roughness is given by (Wong, 1993):

$$\begin{cases} \Omega \le \dfrac{1}{2\pi} cycle/m \Rightarrow S(\Omega) = \dfrac{a}{(2\pi\Omega)^2} \\ \Omega > \dfrac{1}{2\pi} cycle/m \Rightarrow S(\Omega) = \dfrac{a}{(2\pi\Omega)^{1.5}} \end{cases} \tag{5}$$

where a (m^3/cycle) is the roughness coefficient or value of the spectral density at the discontinuity spatial frequency $\Omega = \frac{1}{2\pi}$ cycle/m. Ω_{min} and Ω_{max} are taken as 0.01 and 10 cycles/m respectively. The transformation of spatial natural frequency, Ω, to spatial circular frequency, ω, is given by $\omega = 2\pi\Omega$. The value of a depends on the road condition and is given in Table 1.

Table 1 – Classification of Road Roughness Proposed by ISO

Road Class	**A(Very Good)**	**B(Good)**	**C(Average)**	**D(Poor)**	**E(Very Poor)**
a **(m^3/cycle)**	$a < 8 \times 10^{-6}$	$8 \times 10^{-6} \leq a < 32 \times 10^{-6}$	$32 \times 10^{-6} \leq a < 128 \times 10^{-6}$	$128 \times 10^{-6} \leq a < 512 \times 10^{-6}$	$512 \times 10^{-6} \leq a < 2048 \times 10^{-6}$

COST323 (1999) recommends a WIM site with an International Roughness Index (IRI) lower than 2.6 mm/m for accuracy class B, which is equivalent to an ISO roughness coefficient lower than $a = 4 \times 10^{-6}$ m^3/cycle, this is, a 'very good' road profile. These estimations of accuracy are generally conservative and below the level that could be expected when using a large array of sensors.

2.3 Axle Forces Applied to the Pavement

Figure 2 shows the instantaneous dynamic forces derived from Equation (3) for K = 400 kN/m, viscous damping C = 20 kN*s/m and M = 800 kg. A theoretical 'good' road profile ($a = 16 \times 10^{-6}$, IRI ≅ 4.6 mm/m) was adopted for testing the vehicle response as this will tend to have less pronounced spatial repeatability than rougher pavements. It can be seen how dynamic impact factors increase significantly at the higher velocity.

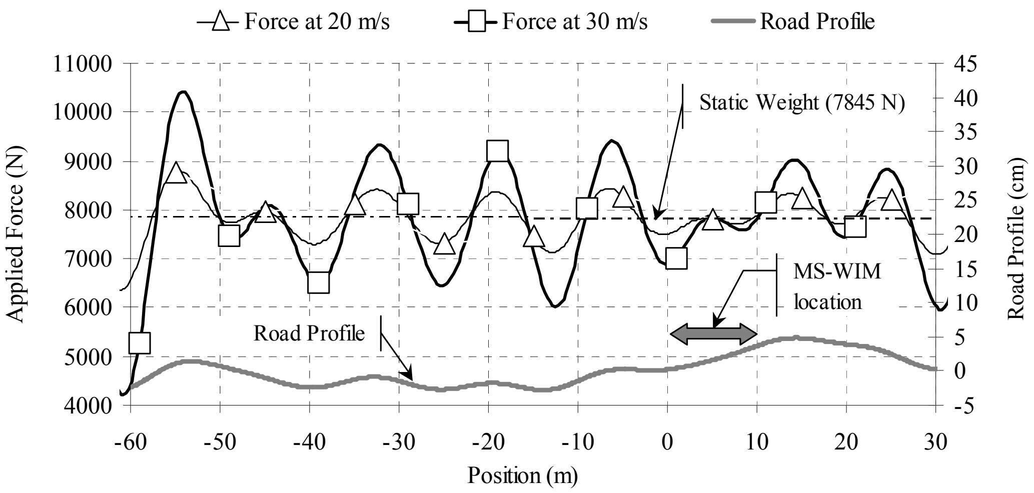

Figure 2 – Applied Dynamic Forces in a 'Good' Road Profile

3. Functional Network for Multiple-Sensor Weigh-In-Motion

In NN's, a number of different topologies are tested until errors are considered to be sufficiently small. In FN's, the initial structure is selected based on the properties of the problem being analysed. Castillo et al. (1998) adjust this topology using functional equations, which are the main tool for producing an equivalent simplified structure. The neuron functions are estimated by approximating the given data to a set of appropriate functional families. A least squares fitting technique is then used to obtain the optimal coefficients of the neuron functions that minimise the error of the approximation. Finally, a training set of data is used to check that the solution provided by the FN and the selected family of approximating functions is satisfactory.

In the WIM problem described in Section 2, the dynamic forces are governed by a second order differential equation. Castillo has shown that the solution of the k^{th} order differential equation can be formulated as:

$$y_{j+k} = \sum_{i=1}^{k} a_i y_{i+j-1} + \sum_{i=k+1}^{k+m} a_i \Phi_{i-k}{}^{j} \tag{6}$$

where y_j is the value of the variable y at time step j, a_i are constant coefficients and m is the number of basic functions Φ selected to model the problem. For the differential equation of motion, $k = 2$ and Equation (6) can be expressed as:

$$y_{j+2} = f_{j+2} + g_{j+2} \tag{7}$$

$$f_{j+2} = a_1 y_j + a_2 y_{j+1} \tag{8}$$

$$g_{j+2} = a_3 \Phi_1{}^j + a_4 \Phi_2{}^j + ... + a_{i+2} \Phi_i{}^j + ... + a_{m+2} \Phi_m{}^j \tag{9}$$

The FN defined by Equations (7), (8) and (9) is summarised in Figure 3.

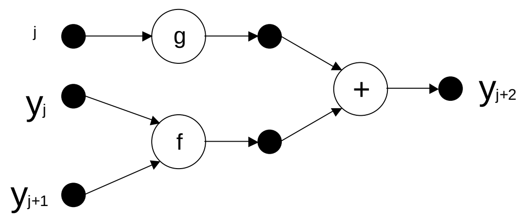

Figure 3 – Functional Network

Since the applied force is related to the relative displacement of the spring, WIM measurements at sensors j, ($j+1$) and ($j+2$) are assumed to be governed by the same topology as the variable y in Figure 3. The parameters $a_1, a_2, ..., a_{m+2}$ can be obtained by minimising the error function E given by the squared difference between measured and predicted WIM outputs:

$$E = \sum_{j=1}^{n-2} \left[\tilde{y}_{j+2} - y_{j+2} \right]^2 \tag{10}$$

where $\tilde{y}_{j+2}$ is the WIM measurement at WIM Sensor $j+2$ and n is the number of sensors. By substituting Equations (7), (8) and (9) into Equation (10):

$$E = \sum_{j=1}^{n-2} \left[\tilde{y}_{j+2} - a_1 y_j - a_2 y_{j+1} - a_3 \Phi_1{}^j - a_4 \Phi_2{}^j - \ldots - a_{m+2} \Phi_m{}^j \right]^2 \tag{11}$$

Then, a minimum condition is imposed by:

$$\frac{\partial E}{\partial a_i} = 0; \quad i = 1, 2, \ldots, (m{+}2) \tag{12}$$

The calibration of the FN consists of finding the unknown functions, Φ (polynomial, trigonometric, logarithmic…) that best fit the measured data. In this case, the initial basic functions are assumed to be trigonometric such as:

$$\{\Phi_1, \Phi_2, \Phi_3, \Phi_4, \Phi_5 \ldots\} = \{1, sin(t), cos(t), sin(2t), cos(2t), sin(3t), cos(3t) \ldots\} \tag{13}$$

If three basic functions are considered ($m = 3$), $\{y\}$ and $\{a\}$ can be related through:

$$\begin{Bmatrix} y_3 \\ y_4 \\ \ldots \\ y_i \\ \ldots \\ y_n \end{Bmatrix} = \begin{bmatrix} y_1 & y_2 & 1 & \sin(0) & \cos(0) \\ y_2 & y_3 & 1 & \sin(dt) & \cos(dt) \\ \ldots & \ldots & 1 & \ldots & \ldots \\ y_{i\text{-}2} & y_{i\text{-}1} & 1 & \sin((i-3)dt) & \cos((i-3))dt) \\ \ldots & \ldots & 1 & \ldots & \ldots \\ y_{n\text{-}2} & y_{n\text{-}1} & 1 & \sin((n-3)dt) & \cos((n-3)dt) \end{bmatrix} \begin{Bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{Bmatrix} \tag{14}$$

or:

$$\{y\} = [F]\{a\} \tag{15}$$

Finally, the parameters $\{a\}$ are obtained by combining Equations (12), (14) and (15) and are given by Equation (16) (Rajasekaran, 2004):

$$\{a\} = \left[[F]^T [F]\right]^{-1} [F]^T \{\tilde{y}\} \tag{16}$$

Figure 4 compares the simulated WIM forces using Equation (3), noise not taken into account – with the forces predicted by a FN made of three basic functions when using 10 sensors spaced at 1 m, 20 sensors spaced at 0.5 m and 40 sensors spaced 0.25 m. These forces correspond to the simulation run at 30 m/s of Figure 2, and all three FN's were able to match the simulated forces accurately.

The static axle weight, *Mg*, can be obtained by generating artificial values using the equations of the FN and averaging all values. For the example illustrated in Figure 4, the errors in estimating the static weight were –3.14%, –3.48% and –1.55% for FN's based on 10, 20 and 40 sensors respectively. Accuracy for FN's will generally increase with a higher number of sensors. A simple average of all WIM outputs resulted in higher errors of –4.34%, –4.06% and –3.94% based on 10, 20 and 40 sensors respectively. During the calibration procedure a number of runs will be available and a multiplying factor can be obtained to compensate for any bias in the predicted results.

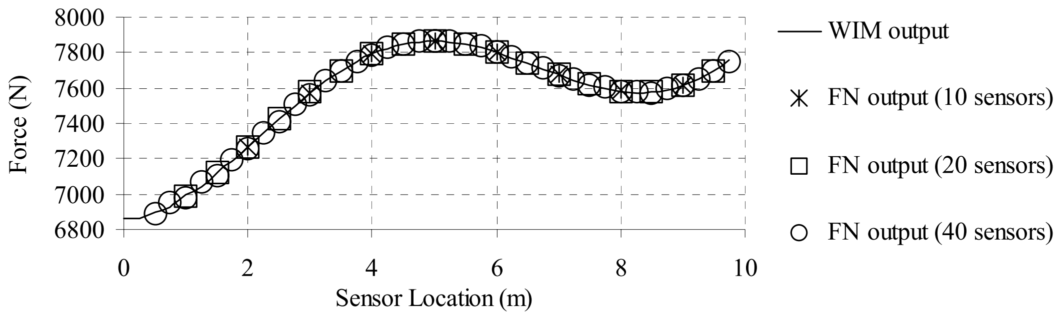

Figure 4 – Axle Forces Predicted by Functional Network

4. Theoretical Testing

In order to test the effectiveness of the algorithm, dynamic forces were simulated for a number of axle models passing over a numerically generated 'good' road profile (Section 2). Speed [20 to 30 m/s], mass [400 to 1200 kg], stiffness [200 to 800 kN/m], damping [10 to 40 kN*s/m] and starting position on the pavement were randomly varied for every simulated run. A total number of 300 simulation runs was divided into three sets: 100 for training and fitting the parameters of the MS-WIM algorithm, 100 for validating the training and the remaining 100 for testing. The multiple-sensor WIM system was assumed to consist of an array of 10 sensors equally spaced at 1 m. All sensors were located between x = 0 and x = 9 m in Figure 2, where there is a clear pattern of spatial repeatability that causes impact factors below unity. The simulated WIM measurements were input to three MS-WIM algorithms: a conventional average-based method, a FN algorithm as in Figure 3 (using three basic functions) and a NN algorithm (González et al., 2003).

4.1 Calibration

The average-based method was calibrated by minimising the mean square error between the dynamic loads and the static loads of the training set using a linear regression passing through the origin (Dolcemascolo, 1999). Due to spatial repeatability, WIM sensors tend to systematically under-weigh axles and hence the calibration factor that resulted from applying the average-method was above 1 for each of the ten sensors, 1.07 being the highest. The FN was adjusted as described in Section 3: a family of trigonometric functions was chosen as the optimal to define the WIM outputs and a calibration factor was also obtained.

The type of NN used was a multilayer feedforward neural network with backpropagation. All neurons were arranged in three layers: an input layer consisting of 10 neurons (one per WIM sensor), a hidden layer with 3 neurons and the output layer with one single neuron, i.e., the static axle weight. Prior to training, all input and output values were normalised to range from 0 to 1. In order to avoid over-fitting, the training with a learning rate of 0.1 was stopped at 10,000 iterations, after which the sum of squared errors of the validation set started to increase. The topology of the NN, including final threshold values and connection weights for the paths linking hidden and output layers, is represented in Figure 5.

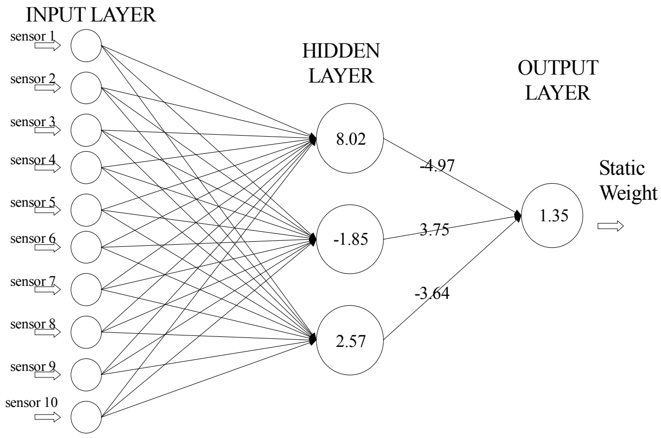

Figure 5 – Neural Network

4.2 Testing

Figure 6 compares the relative errors in % obtained by the simple average, FN and NN algorithms when estimating the static axle weight for the 100 runs of the test set of data.

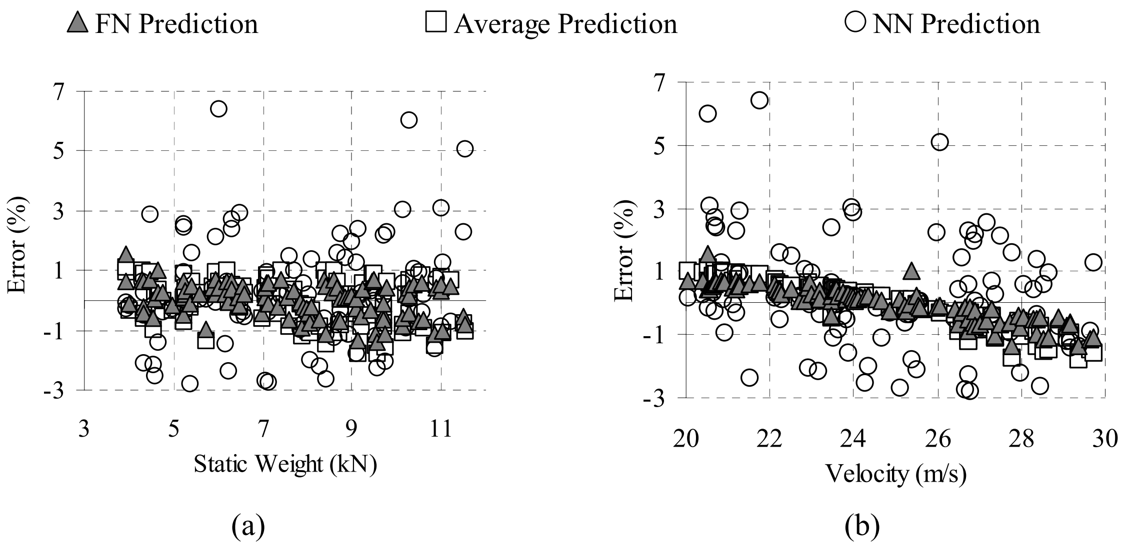

Figure 6 – Relative Errors (%) by Functional Network, Average Method and Neural Network MS-WIM Algorithms versus (a) Static Weight and (b) Velocity

Higher errors take place at higher speeds for average and FN algorithms, but results from the NN are more scattered. The maximum error obtained by the average and NN methods was -1.77% and 6.4% respectively. The FN contained only 5 parameters ($m = 3$), as compared with the NN which contained 37 parameters for 3 hidden neurons, and the maximum error was 1.55%. The correlation coefficient obtained between values using the FN and the actual values was 0.9998, whereas the correlation coefficients obtained using the average and NN methods with the actual values were 0.9995 and 0.9986 respectively. In any case, the FN appears to be the most accurate of the three MS-WIM algorithms, although only by a small margin.

Table 2 gives COST 323 accuracy class for each MS-WIM algorithm for the criterion of single axle and extended repeatability conditions (r2) (COST 323, 1999). All algorithms fall into class A(5), but the FN ($\delta_{min} = 1.4$) and average methods ($\delta_{min} = 1.8$) are somewhat more accurate than NN's ($\delta_{min} = 4.2$). NN's are very sensitive to the normalisation range (González et al. 2003) and while [0-1] was selected in this exercise, other ranges could affect NN's accuracy significantly.

Table 2 – Accuracy Classification

(**n**: Total number of vehicles; **m**: mean; **s**: Standard deviation; π_0: level of confidence; δ: tolerance of the retained accuracy class; δ_{min}: minimum width of the confidence interval for π_0; π: Level of confidence of the interval $[-\delta,\delta]$)

	Relative error statistics				**Accuracy calculation**			
MS-WIM Algorithm	n	m (%)	s (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	π (%)
Functional Network	100	-0.01	0.58	96.9	A(5)	8	1.4	100.
Average Method	100	-0.03	0.77	96.9	A(5)	8	1.8	100.
Neural Network	100	0.28	1.75	96.9	A(5)	8	4.2	100.

In addition to the static weight, the output of MS-WIM systems contains other useful information on vehicle and road characteristics. Theoretically, a FN could be used to extract these characteristics by relating the a_1y_j, a_2y_{j+1}, $a_3\Phi_1^{\ j}, a_4\Phi_2^{\ j},\ldots,a_{m+2}\Phi_m^{\ j}$ components of the FN (Equations (7), (8) and (9)) to the Mg, $\left(-M\dfrac{d^2r}{dt^2}\right)$ and $\left(-M\dfrac{d^2y}{dt^2}\right)$ components of the interaction force (Equation (3)).

5. Conclusions

This paper has focused on a powerful generalisation of artificial neural networks known as functional networks. Unlike neural networks, where transfer functions are fixed and weights are adjusted during the learning process, neural functions are unknown and estimated during the learning process. A functional network specific to the MS-WIM problem has been derived. The results of the functional network have compared favourably to other MS-WIM algorithms. There has been a modest improvement in accuracy of calculated static weights, but the algorithm needs to be tested in other scenarios where noise and road roughness are more significant. The influence of the number of sensors and sensor spacing on accuracy and the possibility of identifying vehicle dynamic characteristics also require further investigation.

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PERFORMANCES OF A LS-WIM SYSTEM BY TESTING

   

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Abstract
In France, overloading enforcement is currently performed by means of static weighing. In order to increase enforcement efficiency, some automated tools are needed. Within this context, the Laboratoire Central des Ponts et Chaussées was involved in the performances evaluation of a low-speed weigh-in-motion system developed by the French manufacturer CAPTELS. A recent field experimentation was carried out according to the International Organization of Legal Metrology (OIML) recommended test plan. Experimentation conditions and results will be described and analysed.

Key words : Low-speed weigh-in-motion, enforcement, overloading, experimentation.

Résumé
Actuellement, seules les pesées statiques des essieux des véhicules permettent le contrôle des surcharges de poids lourds. Afin de répondre aux besoins d'améliorer l'efficacité des contrôles, des outils automatiques sont nécessaires. Dans ce contexte, le Laboratoire Central des Ponts et Chaussées a été impliqué dans des essais d'évaluation d'un système de pesage en marche à basse vitesse développé par la société française CAPTELS. Une expérimentation récente a été conduite sur ce système selon le plan d'expérience recommandé par l'Organisation Internationale de la Métrologie Légale (OIML). Les conditions de l'expérimentation et les résultats obtenus seront décrits et interprétés.

Mots-clés : Pesage en marche à basse vitesse, LS-WIM, contrôle, surcharge, expérimentation.

低速動態地磅系統之績效測試

摘要
法國是以靜態地磅所量得之重量資料進行超載之執法工作，為提昇執法效率增加一些自動化工具是必要之工作。基於上述背景，LCPC(the Laboratoire Central des Ponts et Chaussées) 針對法國製造廠商 CAPTELS 公司所發展之低速度動態地磅系統（low-speed weigh-in-motion system）進行績效評估。並依據 OIML(the International Organization of Legal Metrology)所建議之實驗計畫進行現地實驗。本篇文章將針對實驗之狀況以及分析所得結果進行說明及討論。

關鍵字：低速動態地磅系統、執法、超載、實驗

1. Introduction

Overloaded trucks induce road unsafety, early infrastructure damage, and unfair competition between transport companies and transport modes.
In France, enforcement is currently performed by means of static weighing. Truck axles static weighing are delicate operations during which operators have to check that each wheel is correctly located on the plate, and that the truck driver doesn't use brakes dry friction to unload the axle being weighed. This operation is time and money costly.
Budget restrictions led to a 76% diminution of the static weighing numbers during the past 20 years (Figure 9) (Boutillier and Carrez, 2004).

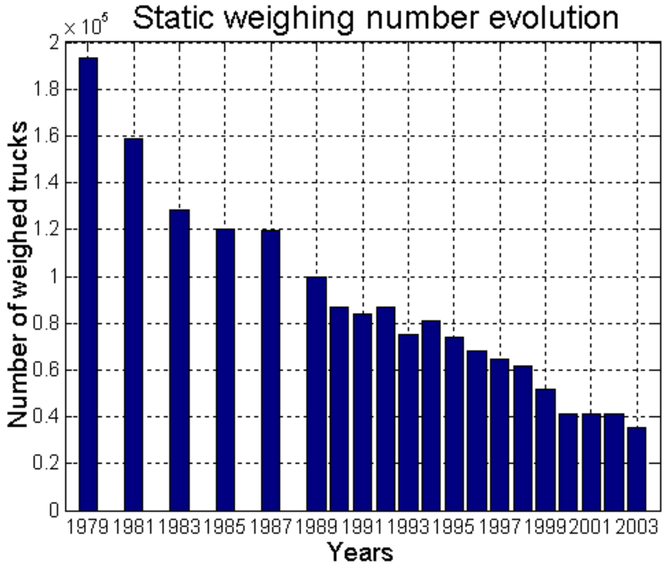


Figure 9 - Evolution of the annual number of static weighing

While the static weighing frequency decreases, statistics from French SIREDO network (composed of 48 traffic data analysis stations) showed a 16% increase of the trucks number between 1991 and 1999.
In order to keep enforcement dissuasive, efficiency needs to be improved, by means of automatic weigh-in-motion (WIM) systems (Marchadour and Duquesne, 1995).
Low-speed WIM (LS-WIM) allows accurate static weight estimation, as trucks-pavement dynamic interaction is weak under approximately 15 km/h. The system is installed on a dedicated area, and trucks have to be intercepted from the traffic by police officers or Variable Message Signs (VMS). The weighing time could be significantly reduced compared to the static weighing time, thanks to the automation, and voluntary axles unloading (with brakes dry friction) would be avoided as vehicles speed has to remain constant (Marchadour, 1998).
International Organization of Legal Metrology (OIML) published a draft recommendation (OIML, 2004) for automatic weighing instruments homologation. This recommendation will be used by French legal metrology services (Sous-Direction de la Métrologie (SDM) from the French Ministry of Industry and Laboratoire National de métrologie et d'Essais (LNE), notified body for French legal metrology) to evaluate LS-WIM system performances and possibly deliver a certificate for enforcement application.
Within this context, French Public Works Research Laboratory was involved in a field experience on the LS-WIM system developed by the French company CAPTELS.

2. LS-WIM system and test site

CAPTELS LS-WIM system is composed of two weighing plates instrumented with strain gauges load cells, and data acquisition electronic (Reversat-Brulant et al., 1998).
The system's weighing range is : 500 to 20 000 kg, with a 20 kg scale interval. Temperature range is : -10 to 40°C.
Some parameters can be adjusted depending on the required application. Here, speed range was chosen as 1 to12 km/h, and acceleration range as -0.4 to 0.4 m.s².
Once these parameters are fixed, the system delivers error message when trucks runs are not within the specified speed and accelerations.
The system records :

- date and time,
- vehicle silhouette,
- axle weight,
- group of axles weight,
- gross vehicle weight,
- vehicle length,
- mean speed and each axle's speed,
- mean acceleration and each axle's acceleration,
- overloading rate (if legal limits are provided).

The test site is located in Châlon-sur-Saône, in a harbour zone, close to a commercial weigh-bridge. The site is equipped with a 36meters long concrete slab with two pits in the middle, dimensioned to receive the weighing plate (Figure 10 and Figure 11). The concrete slab is plane and homogeneous in order to avoid trucks dynamic excitation.

Figure 10 - Weighing plates within the concrete slab

Figure 11 - 2-axles rigid truck weighed at low-speed

3. Test plan

3.1.Truck sample

The truck sample was chosen according the OIML recommendation (OIML, 2004). Trucks are representative of the French traffic, and different axles configuration, tractor/trailer linkage and suspension types were tested.

Axles loads are covering as much as possible the weighing range of the LS-WIM system (Figure 12).
The truck sample composition is summarised in Table 2.
Truck 1 is a rigid 2 axles truck, Truck 2 is a 5-axles semi-trailer with a tridem, and Truck 3 is a 5-axles draw-bar trailer with a tandem axle.
Truck 4 is a light rigid truck (permissible maximum weight : 3.5 tons). Those light trucks were shown to be often overloaded, and in spite of the expected higher relative error (compared to heavier vehicles), they are needed to be enforced. Truck 5 is a 5-axles semi-trailer vehicle carrying liquid. This vehicle was chosen in order to evaluate the influence of moving liquids within the cistern (which was not fully loaded) on the LS-WIM system performances.

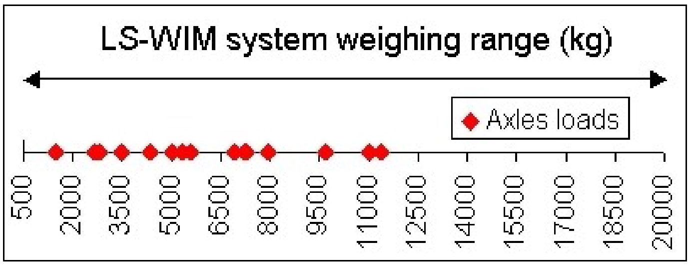


Figure 12 - Axle loads distribution compared to LS-WIM system weighing range

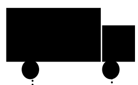
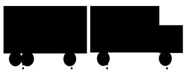
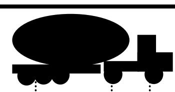
Name	**Truck 1**	**Truck 2**	**Truck 3**	**Truck 4**	**Truck 5**
Silhouette					
Suspensions *	A M	A A M	A A A M	M M	A A M
GW (empty)	9 695 kg	14 585 kg	17 230 kg	2 945 kg	16 725 kg
GW (loaded)	16 945 kg	38 245 kg	39 325 kg	4 155 kg	29 295 kg
PMW **	19 400 kg	38 000 kg	40 000 kg	3 500 kg	38 000 kg

Table 2 - Summary of the truck sample
**A : Air suspension ; M : Mechanical suspension*
** : Permissible Maximum Weight

3.2. Reference weights

Reference weights were defined according to OIML recommendation (OIML, 2004). Measured weights will be compared to these reference weights in order to assess the LS-WIM system performances.

3.2.1. Gross Weight

Each vehicle from the truck sample, with each loading configuration, was weighed twice on the weigh-bridge : once before and once after the test runs. Reference gross weigh GW_{ref} was taken as the mean of the two values.

3.2.2. Single Axles and Group of Axles weight

3.2.2.1. Two-axles rigid trucks (Truck 1 and Truck 4)

Rigid trucks axles are considered by OIML recommendation (OIML, 2004) as the only ones allowing a correct measured static axle weight. The LS-WIM system was used in a static mode to measure Truck 1 and Truck 4 axles weights. Each axle was weighed five times in one direction and five more times in the opposite direction.

The mean value $\overline{Axle_s}$ of those 10 weighing is then calculated, as well as the mean measured gross weight $\overline{GW_s}$ (sum of mean axle weight $\overline{Axle_s}$). Axle weight reference is then taken as :

$$Axle_{ref} = \overline{Axle_s} \times \frac{GW_{ref}}{\overline{GW_s}}.$$

3.2.2.2. Other trucks

Articulated vehicles axles are not weighed statically on an axle load scale. For each axle of each truck in both loading configuration, the mean value of low-speed axle weighing $\overline{Axle}$ is calculated, as well as the mean value of low-speed gross weigh $\overline{GW}$. Axle weight reference is then taken as $Axle_{ref} = \overline{Axle} \times \frac{GW_{ref}}{\overline{GW}}$.

3.3. Test runs

Each vehicle with each loading realised 20 runs at different velocities V :

- 5 runs with 1 km/h ≤ V < 3 km/h
- 10 runs with 3 km/h ≤ V ≤ 10 km/h
- 5 runs with 10 km/h < V ≤ 12 km/h

Some runs were also carried out in order to validate LS-WIM system error detection when the velocity is over 12 km/h or under 1 km/h, or when the acceleration is over 0.4 $m.s^{-2}$.
Speed and acceleration were recorded both with the LS-WIM system and an external system installed on the trucks. The two devices provided very close measurements.

4. Results

Relative errors compared to the reference weight were computed for each truck / loading, and for the three following criteria : Gross Weight (GW), Single Axles (SA), Group of Axles (GoA). Maximum relative errors were also computed for each configuration. Relative errors were used to determine the COST 323 accuracy classes (COST323, 1999).

4.1.Errors analysis

4.1.1. Relative errors

First, LS-WIM system performances with respect to the reference weight were analysed (Figure 13).

As expected, relative errors decrease with the reference weight. Two reasons might explain this phenomena :

- Loaded vehicles at low-speed tend to be less affected by dynamic effects than unloaded vehicles, as it was shown in DIVINE European project (Jacob and Dolcemascolo, 1997).
- For a given system deviation, the relative error increases if the reference weight decreases. Observation of Figure 13 shows a decrease of errors variance when static weights increase, and then a stabilisation at a given variance. Further analysis might allow to determine the sensors error model, probably split into two parts : an independent random one, added to another one correlated to the axle's weight.

An outlier occurrence (circled in orange on Figure 13) was detected by a Dixon test. This value is related to the loaded Truck 2 axle weight with a 9.81 km/h velocity.

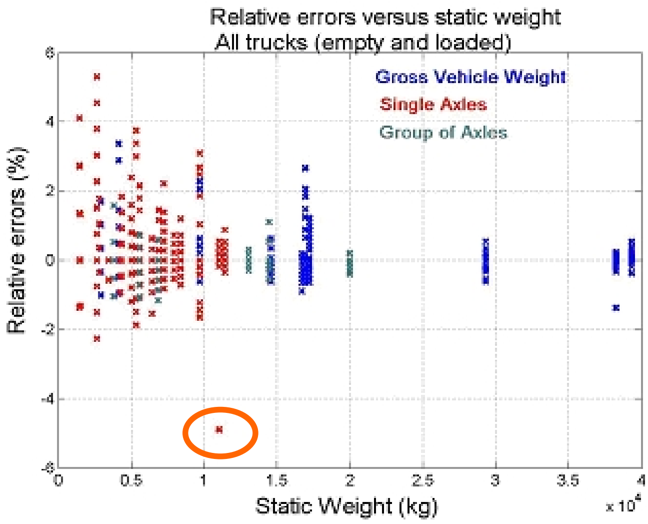


Figure 13 - Relative error distribution with respect to the reference weight

LS-WIM system performances with respect to the vehicle speed were analysed for two sub-samples : rigid vehicles and articulated vehicles (resp. Figure 14 and Figure 15).

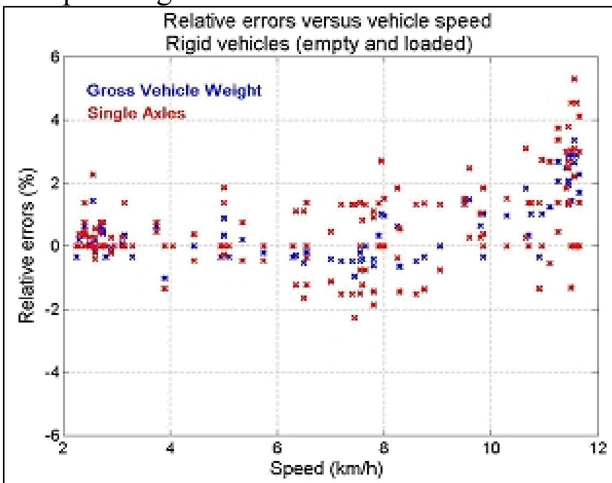


Figure 14 - Relative error distribution with respect to rigid vehicles speed

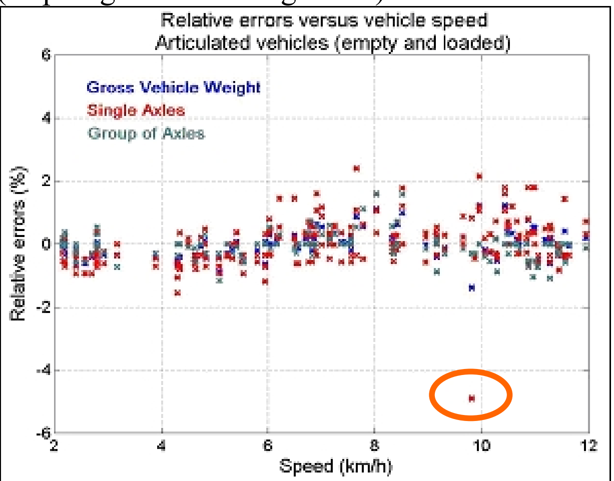


Figure 15 - Relative error distribution with respect to articulated vehicles speed

Rigid vehicles errors on Figure 14, compared to articulated vehicles errors on Figure 15 (again, with the outlier circled in orange) seem especially affected by the vehicle speed. This behaviour is coherent with the analysis carried out on the static weight influence on errors. The lighter vehicles within our sample are indeed the rigid ones, and the two reasons developed before can explain the observed distributions. The different type of reference calculation could also slightly influence the two samples comparison.
Therefore, LS-WIM system performances might be improved if the maximum speed was fixed around 8 to 10 km/h.
Figure 16 shows the percentage of values fulfilling different threshold requirements.
Whatever the observed criterion, the highest errors have very few occurrences. For example, 90.5% of the articulated vehicles single axles are weighed with an error under 1%.

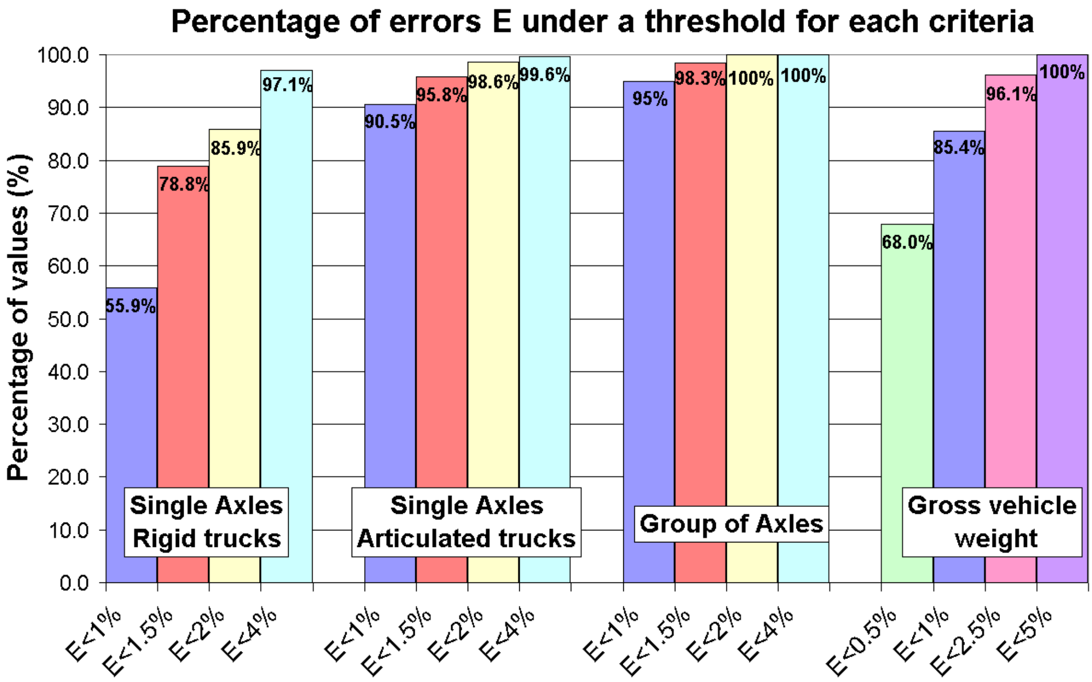


Figure 16 - Percentage of measured values under an error threshold

4.1.2. Maximum relative errors

Maximum relative errors were computed for all vehicles. Results are presented for each criterion on Figure 17.
Gross weights are weighed with an error under 3.5 % (worst case), single axles with an error under 5.5 % (worst case), and group of axles under 2 % (worst case).
As expected, single axles provide higher errors than other criteria. Group of axles or gross weight are indeed computed from the sum of individual axles, and random part of errors are then averaged.
For the reasons already mentioned, rigid vehicles have higher maximum relative errors.
When eliminating the outlier from the Truck 2 sample, maximum relative error drops drastically to the lowest level compared to other trucks.

Truck 5 behaviour is unexpected. Liquid movement within the cistern does not seem to affect the dynamic behaviour of the truck, and, by extension, the static weight estimation accuracy.

Figure 18, Figure 19, and Figure 20 show the maximum relative errors that would be obtained for various maximum speed, respectively for gross vehicle weight, single axle, and group of axle criteria.
Little peaks which would look like incoherent are observed, because of the reference weight varying with the considered runs sample.
While group of axles weight doesn't seem much affected by the vehicle speed, single axles and gross vehicle weight would provide maximum errors much lower if the maximum speed was around 8 to 10 km/h instead of 12 km/h.

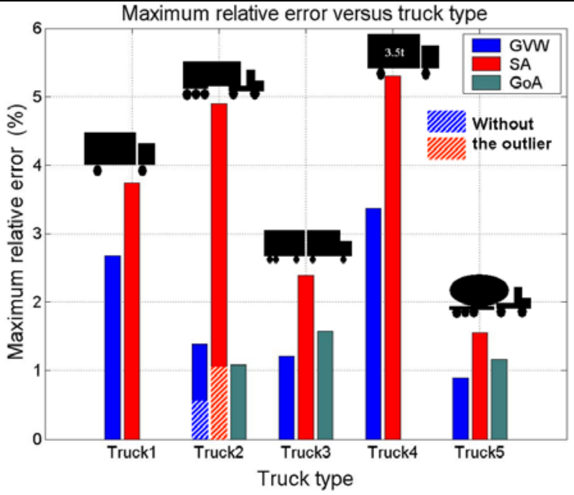


Figure 17 - Maximum relative error versus truck type (max. speed = 12 km/h)

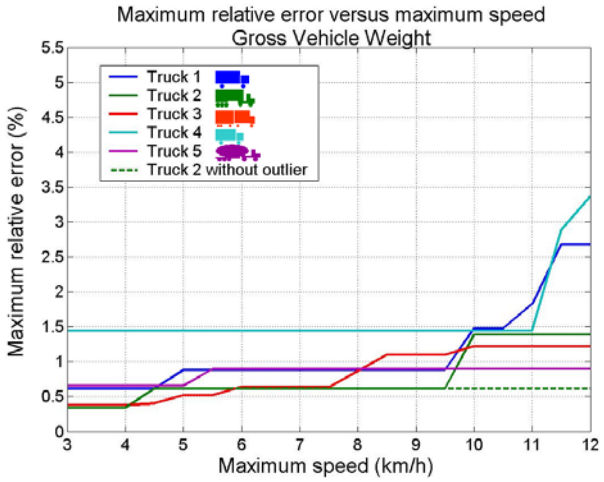


Figure 18 - Maximum Gross Weight relative error with respect to the maximum speed

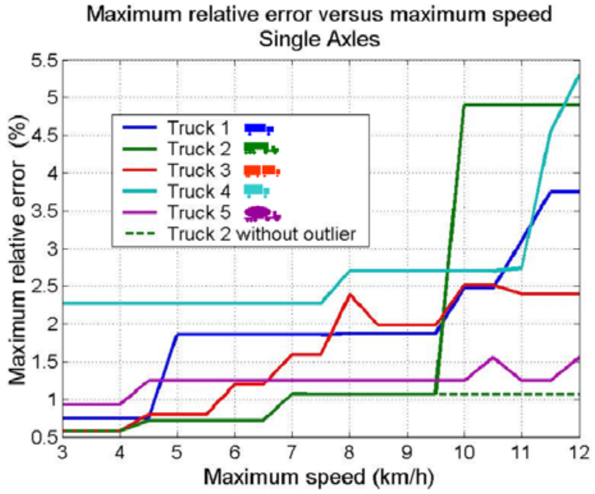


Figure 19 - Maximum single axles relative error versus maximum speed

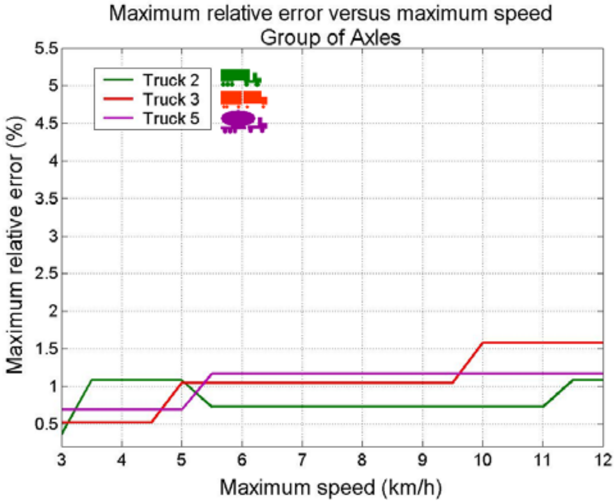


Figure 20 - Maximum group of axles relative error versus maximum speed

4.2. COST323 accuracy classes

COST323 specifications (COST323, 1999) were applied to the measurements in order to evaluate the system performances. Figure 21 and Figure 22 show δ_{min} results for each truck, respectively when maximum speed is 12 km/h and 9.5 km/h. This last velocity was chosen from Figure 18 and Figure 19 observation.

Figure 21 also provides Truck 2 results without the outlier at 9.81 km/h. δ_{min} are not so much affected by the outlier because of the probabilistic COST323 specifications approach. δ_{min} represents indeed the half tolerance interval length for a π_0 confidence level (depending of the sample size and the test conditions).

Comparison of each truck's type accuracy leads to the conclusions already mentioned. However, comparison of the two figures allows to confirm that a maximum speed around 8-10 km/h increases system performances.

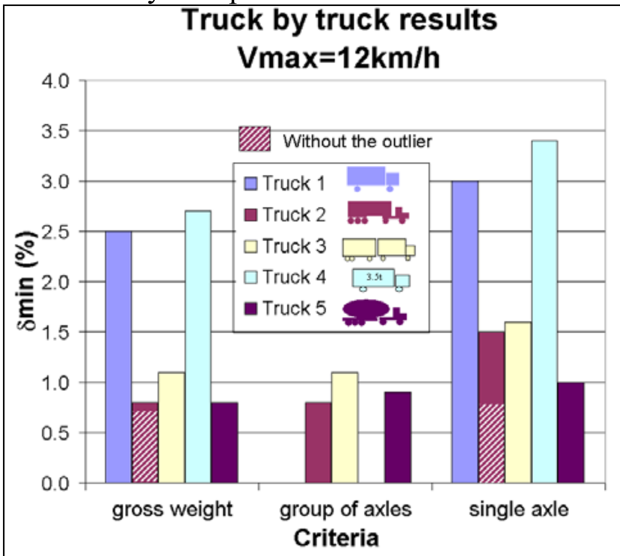


Figure 21 - Obtained δmin for each truck when maximum speed is 12 km/h

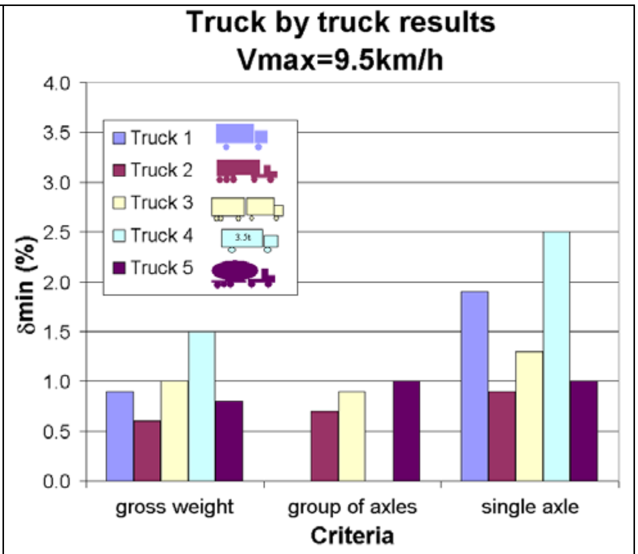


Figure 22 - Obtained δmin for each truck when maximum speed is 9.5 km/h

Detailed results for the whole truck sample are given in Table 3 and Table 4. Again, the performances are confirmed to be significantly increased when the maximum velocity is 9.5 km/h, especially for gross weight (approximately 95.5 % of the errors are within a [-1% ; 1%] interval instead of [-1.8% ; 1.8%], that is a 44% improvement) and for single axles (approximately 96 % of the errors are within a [-1.6% ; 1.6%] interval instead of [-2.2% ; 2.2%], that is a 27 % improvement).

Calculation were performed for the same sample without the outlier, but did not lead to significant differences.

Entity	Number	Mean error (%)	Error std. dev. (%)	π_0	Class	δ_{min}	Accepted Class
gross weight	204	0.17	0.81	95.6	A(3)	1.8	
group of axles	121	-0.04	0.45	95.2	A(1)	1.0	A(3)
single axle	449	0.16	1.02	96.1	A(2)	2.2	

Table 3 - Results for a 12 km/h maximum velocity according to COST323 specifications

Entity	Number	Mean error (%)	Error std. dev. (%)	π_0	Class	δ_{min}	Accepted Class
gross weight	146	-0.05	0.46	95.4	A(2)	1.0	
group of axles	88	-0.05	0.40	94.8	A(1)	0.9	A(2)
single axle	321	-0.02	0.73	95.9	A(2)	1.6	

Table 4 - Results for a 9.5 km/h maximum velocity according to COST323 specifications

Previous trial on CAPTELS LS-WIM system on this test site was carried out in 1998. δ_{min} obtained in similar test conditions (maximum speed around 12 km/h) were 2.0, 2.5, and 2.6 respectively for GW, GoA and SA criteria (Labry et al., 2005). Thus, system's improvement realised by the manufacturer since 1998 is significant. Previous version of CAPTELS LS-WIM system was also evaluated by LCPC with a portable ramp instead of the concrete slab (Dolcemascolo et al. 1998).

5. Conclusions

This experimentation was carried out according to a test plan recommended by OIML (OIML, 2004), and allowed to evaluate CAPTELS LS-WIM system performances. Relative errors analysis was realised with respect to the static weight and the vehicle speed.
Relative errors were shown as higher for lighter vehicles, because of a more scattered dynamic behaviour and a sensor absolute error independent of the weight.
Vehicle speed was also proved to have a significant influence on single axles and gross static weight estimation. However, group of axles were shown as almost independent regarding to the speed or the static weight.
Relative errors distributions (including maximum relative errors analysis) as well as δ_{min} analysis according to COST323 European specifications showed that the system performances could be significantly improved by defining a maximum permissible speed around 8-10 km/h.
Trucks carrying liquids, even if not fully loaded, were weighed with a very good accuracy.
COST323 accuracy classes A(3) was reached for a trucks sample with a speed under 12 km/h, and A(2) for a sample with the speed under 9.5 km/h.
French legal metrology services (SDM and LNE) are currently working on CAPTELS LS-WIM system evaluation and should deliver soon some conclusions with respect to possible enforcement applications.

Acknowledgement

This trial received financial support from the Ground Transportation Division (DTT) from the French Ministry of Equipment and Transportation. Authors are thankful to CAPTELS, owner of the presented data, to the legal metrology services (Sous-Direction de la Métrologie and Laboratoire National de métrologie et d'Essais), to the regional laboratories and directorates from the Ministry of Equipment and Transportation (Laboratoire Régional de l'Ouest Parisien, Centre d'Etudes Techniques de l'Est, Direction Régionale de l'Equipement de Bourgogne), which all were significantly involved in this experimentation.

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IM (INTEGRATED MATRIX) WIM SENSOR AND FUTURE TRIALS

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Abstract
Future "Fully Automatic Enforcement Systems" for truck overload will require more precise and reliable WIM. New modular mini force sensors (Integrated Matrix WIM Sensor) based on strain gauge technology in a flat steel architecture are developed. Long term stability, higher precision and a data quality including new parameters (tire foot print, pressure distribution, lateral wheel position, axle width) can be achieved. The system structure and concept of this new WIM sensor, the planning of a new Berlin WIM test site by DLR Test of fully automatic WIM Enforcement and the "Transportkraft" as a new traffic variable (incl. transported mass) will be presented too.

Keywords: Weigh-in-Motion, Automated WIM, Enforcement, Weighing Sensors, Transportkraft.

Résumé
Les futurs „Systèmes de Détection entièrement automatisés" pour la surcharge de camions ont besoin d'une méthode plus précise et plus sure sûre pour le pesage en mouvement marche (WIM). Nous présenterons des nouvelles nouveaux capteurs de pesage miniaturisés modulaires (Integrated Matrix WIM Sensor) fondés sur des jauges de contrainte et intégrés dans des boîtes métalliques. Ces capteurs atteindront une stabilité à long terme et des données plus précises y inclus compris de nouveaux paramètres (empreinte de pneu, distribution de la compression, situation position lateral latérale danse la voie, largeur de empattement ld'essieu). La structure du système de ce nouveau capteur WIM seront est présentées ainsi qu'un nouveau emplacement site d'essai opéré par le DLR/ Berlin. Une nouvelle variable et la dite « Transportkraft » (« Force de transport ») est introduite pour comme nouvelle modélisation modéliser la circulation y compris le poids.

Mots-clés: Pesage-en-Mouvementmarche, WIM Pesage en Marche Automatisé, Détection, Capteur de Pesage, Transportkraftforce de Transport.

矩陣整合型之動磅地磅感測器及測試

摘要：
未來貨車超載之全自動執法系統需要更精確與可靠的動態地磅系統支援。以應變計技術為開發基礎並在平鋼板結構上組裝之新型迷你力感測器(以矩陣排列之應變計整合形式之動態地磅感測器)已被開發。新感測器可達到長期的穩定性、較高的精確度以及提供新的參數(包括胎印、壓力分佈、側向輪胎位置以及軸寬等)。文章中並包括新型動態地磅感測器之系統結構及概念、一個全自動動態地磅執法（柏林動態地磅測試站）計畫，以及將交通量及運輸重量作為新交通量參數的概念。

關鍵字：動態地磅、自動動態地磅、執行、重量感測器、交通紀錄

1. History and Background

Weigh in Motion (WIM) has today a history of over 40 years, starting with weight data collection of trucks and its axles for statistical purposes required for pavement design and maintenance. To protect the road infrastructure from damage and to reduce wear and tear, in the 1970's the first semi-automatic weighing stations consisting of pre-selection WIM scales and downstream axle weighbridges for enforcement in rest- or parking areas were designed, built and are operated until today. Measurement technologies for WIM sensors started with load cells, steel plates with strain gauges and were supplemented with low cost sensors using piezo, crystal or optical fiber technology (Jacob, 1999).

Due to the high infrastructure and operation costs of these semi-automatic weighing stations, investigations for fully automatic overload enforcement systems were initiated in recent years: WIM sites with multiple integrated sensor technologies were built and special algorithms were applied to the measurement data with the expectation to achieve higher weight accuracies than with one single sensor technology (Sainte-Marie et al., 1998; Stergioulias et al., 1998; Cebon, 1999; Dolcemascolo et al., 2002, Labry et al., 2004). Test sites with Multiple Sensor (MS) WIM arrays were built with different sensor technologies in France (Dolcemascolo, 1999), Germany (Balz/Opitz, 2002), UK the Netherlands and many other countries.

To date, no MS-WIM system has been reported in the literature to have achieved Class A(5) accuracy - but in class B+(7) - in accordance with the COST 323 specification (COST323, 1999). The accuracy of an MS-WIM array is related to the accuracy of the individual sensors. The authors have therefore developed the new sensor with the objective of achieving a more accurate sensor than existing technologies which can be used in MS-WIM arrays for fully automatic enforcement. A further objective is a sensor with long term stability in calibration and operation. Besides the aspects of road protection and lifetime extension, which become more and more important due to reduced budgets available for road authorities and increasing privatization of roads, traffic safety and socio-economic effects are important potential advantages of effective automatic enforcement technologies.

The most important goals for the new generation of WIM Sensors are therefore:

- Higher accuracy and initial certification of the sensor
- Stability of measurement (bias and calibration)
- Easier and transparent calibration procedures
- Easier sensor installation and replacement with shorter road closures
- High speed WIM certification procedures

These new requirements in precision, reliability, installation and operability are a challenge for WIM design engineers and require the use of modern measurement, processing and high integration technologies. This paper presents an innovative WIM sensor architecture based on mini WIM sensors organized in a matrix with an embedded digital processing technology using modern bus structures, ASICs and RISC processors.

2. Selected Experience and WIM Technology Status

The TOP TRIAL project (Balz/Opitz, 2002), sponsored by the EU and the German ministry of transport BMVBW investigated multiple WIM sensor arrays using bending plates and piezo-quarz sensors (Figure 1). After nine months of test site construction, many on-site tests were performed under real world traffic conditions in 2000 including investigations of over 10 different algorithms in a one year period.

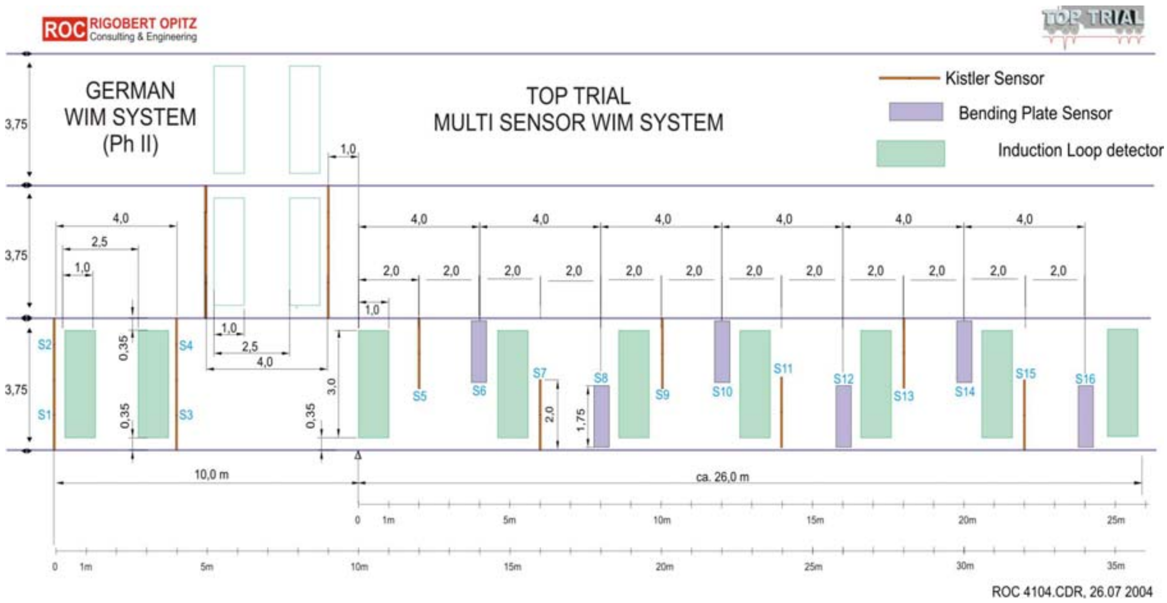

Figure 1 - TOP TRIAL WIM Multi Sensor Array

Experience: shortly after the initial calibration, the WIM systems showed in the following days deviations in sensitivity of a few percent – too high for the usage in fully automatic WIM enforcement systems and not to be compensated by the best algorithms.

The second problem was stability, during the 12 months operation time all piezo-quartz sensors had to be replaced. The German project “Achslasterfassung Phase II” started in 2001 with 11 WIM sites had the same problem concening sensor durability. While the first WIM sites were going through a preliminary acceptance test, it turned out that more and more WIM sensors failed and had to be replaced.

3. Draft Specification IM-WIM (Integrated Matrix WIM)

As a first step the most important user needs and requirements for the new generation of WIM sensors and systems were analyzed:

- High accuracy of the WIM sensor
- Calibration stability for 12 months
- Certification for HS WIM enforcement achievement
- Flat installation in the first pavement layer without excessive road destruction
- Easy installation, maintenance and repair

- Short time for road closures to avoid traffic disturbances
- Consideration of safety issues
- New parameters for road pavement deterioration modeling and design
- Scalability in performance and size

Due to the fact that normally the WIM sensor costs are about less than 20% of the total system costs of a WIM site - road closures, maintenance and later repairs represent the main cost factors - and that future enforcement systems have to achieve a ROI (return of investment) of 6-12 months, the emphasis in the new sensor design was put on higher data quality and stability, rather than low sensor cost. The new functional and technical requirements of the new IM (Integrated Matrix) WIM Sensor design are therefore:

- Provision of additional WIM parameters - measured by a raster sensing technology (currently a 4 cm measurement raster is used) - like tire foot print, tire pressure distribution, transverse location of wheels in lane, axle width, lane rutting parameters combined with a higher precision of weight measurement (in static as well as in dynamic operation) to be achieved with this new IM-WIM concept.
- The new WIM sensor has to operate in both static and dynamic mode. Static weight measurement performance of the weight measurement sensor should be clearly under 1% and the sensor has to be certified by weight and measures. To use this certified weight sensor in dynamic mode in the road, a long term stability of the measurement accuracy is required. This new approach means that we provide a static approved weight sensor with guaranteed measurement performance facilitating the dynamic approval for enforcement. For the approval of dynamic weighing, only the dynamic vehicle effects caused mainly by road unevenness need to be considered.
- A/D conversion of the measurements as close to the sensors as possible (embedded in the sensor) with a minimum of analog circuitry to avoid drift and temperature errors.
- High speed data interface via a CAN bus network and USB interface.
- Exchangeability of single sensor modules using a “quick-release fastener” like changing the wheel of a car.

4. IM-WIM Sensor: Concept and Architecture

The idea to build a matrix network consisting of highly precise, stable and cooperative mini weight measurement points implied the necessity to process up to 278 measurement points per IM WIM sensor (plate version) in real-time. The analyzed and selected external measurement sample rate for truck speeds up to 120km/h was set at 2000 Hz (the inner sample rate used by the sensor ASICs is much higher and filtering algorithms are applied), which is at least 5 times higher than used in current bending plate WIM with the inherent problem to get the global maximum peak value. This requirement results in a smart sensor with an in-sensor A/D signal conversion by special ASICs and the use of new RISC processors directly embedded in the sensor.

Figure 2 illustrates two different weight capturing sensor elements are under design and evaluation: mini sandwich shear beam (SKA) and mini bolt pressure (MBP) sensors with strain gauges (initially glued and later produced by thin film technology).

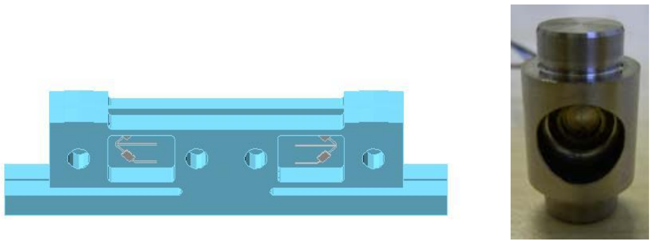

Figure 2 – Example of a SKA Shear Beam and Bolt Pressure Sensor

The electronic structure design was encapsulated in the sensor body to enable short and direct cabling from the strain gauges to the ASICs for A/D conversion and initial signal preprocessing. Immediately measurements are available as digital signals for interim storage, filtering and readout via a SPI data and control bus (Figure 3).

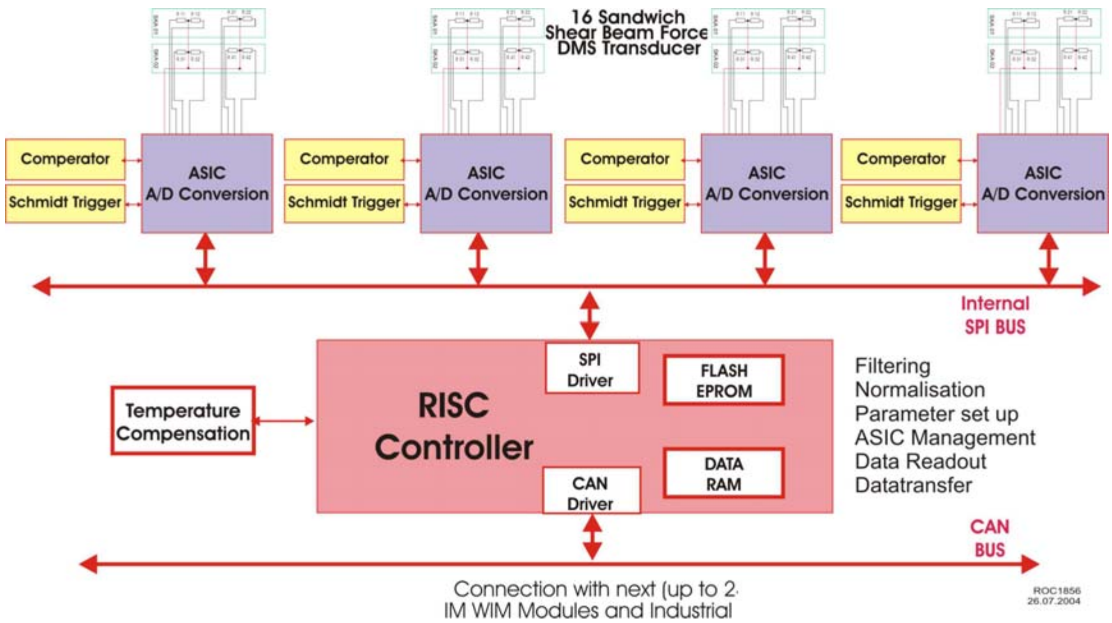

Figure 3 – IM WIM Embedded Electronic Diagram

A RISC controller coordinates the four ASICs and links the sensor module with its 16 measurement points to the next WIM sensor module or the roadside PC via a CAN Bus (up to 276 links allowing different WIM site layouts and configurations) including the power supply.

The mechanical structure designed (Figure 4) uses modular elements produced completely in high quality stainless steel. Each sensor element (bar sensor version) has a width of 60 mm in the driving direction and a length of 320 mm. This allows different sensor surface configurations such as bar sensor or even as a plate surface with 3 or more sensor modules in the driving direction. The sensor with a height lower than 35 mm is flat and protected on top by a wearing layer.

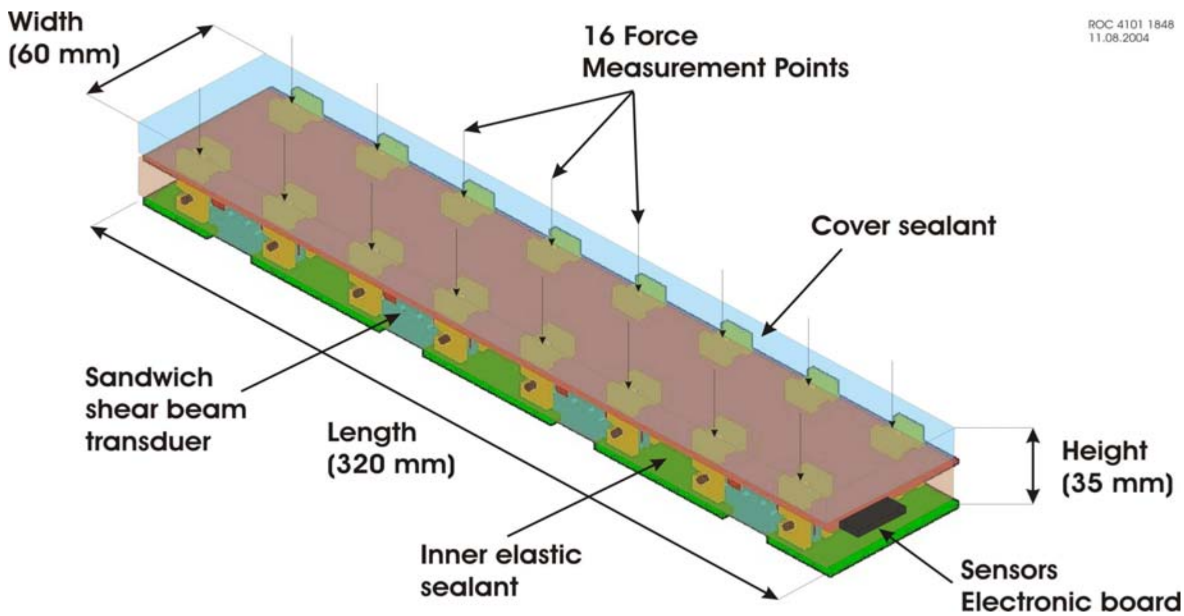

Figure 4 – IM WIM Module 32 cm Mechanical Design

5. Installation

Installation in road (Figure 5) uses the proven installation frame concept (also stainless steel) embedded in cast concrete. Easy installation or even later exchange of the individual sensor modules can be achieved via 6 fast screwing connections in only a few minutes.

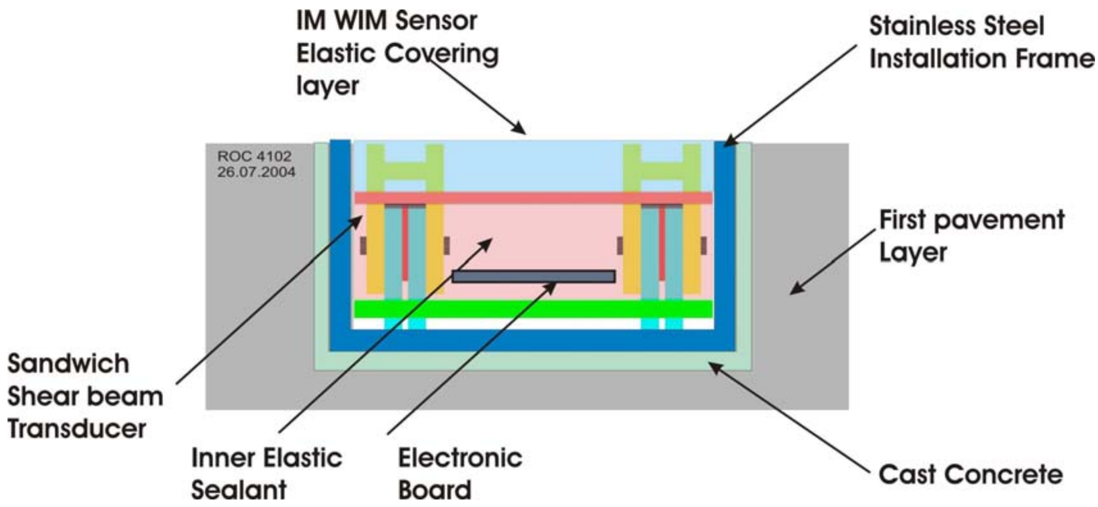

Figure 5 – IM WIM Module 32 cm Roadside Installation

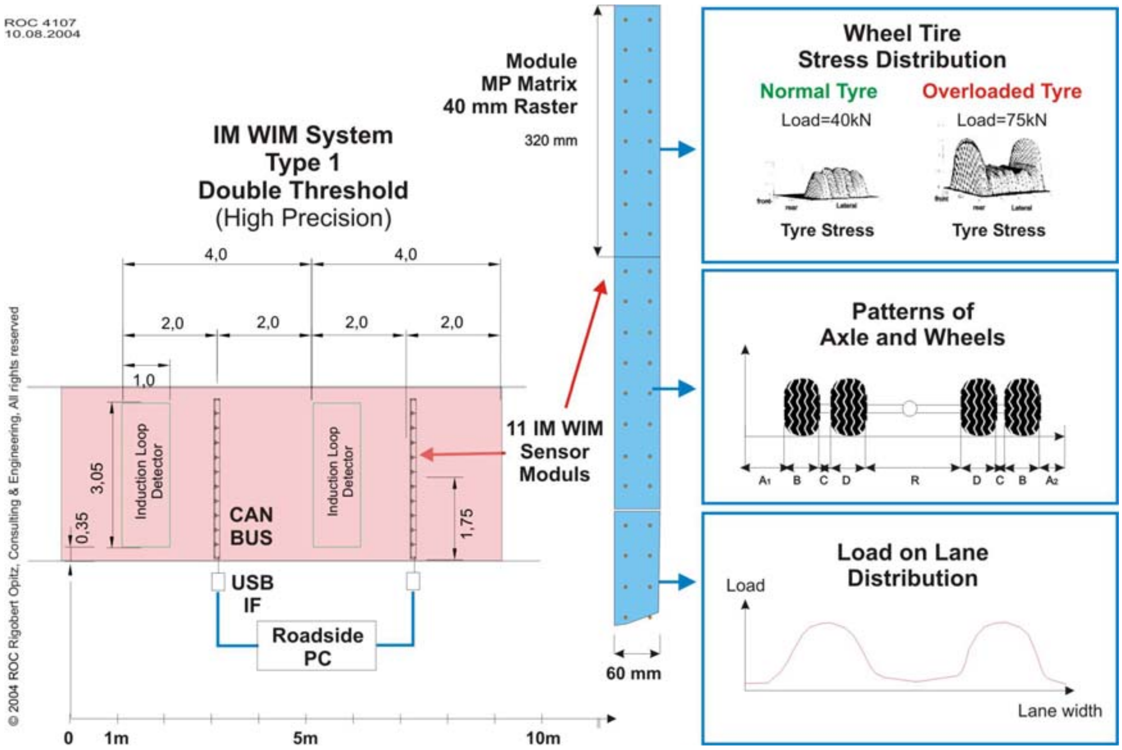

Figure 6 – IM WIM System Layout and Data Provision

6. Test site description (DLR Berlin) and layout

The German Aerospace Center (DLR) is Germany's space agency with nearly 5.000 employees an has extended its activities to include transport research. In January 2000, the Institute of Transport Research (IVF) at Berlin was founded. DLR-IVF has established itself as an independent center of excellence for transport research. The focus is the inclusion of new traffic instrumentation techniques, new kinds of traffic data collection (e.g. fully automatic enforcement, local measurement systems, vehicle probe data) to a harmonisation of traffic flows, for an integrated enforcement, to increase road safety and to an improved utilisation of existing capacities.

Transport Information Science is dealing with the acquirement of data and generation of knowledge. The challenge lies in the development of high-grade models for the forecasting, visualisation, and reproduction of complex processes in transport. The Institute runs a measuring section and experimental test road for traffic detection.

The Test site Berlin Adlershof with a linked traffic tower is currently in preparation by DLR engineers. The test site, with a length of 1300 m, is situated in the south of Berlin, installed in the access to the Autobahn 113 (Berlin ring road) with a future DTV of 80.000 vehicles per day. This laboratory serves two purposes: traffic data collection and the deployment of different units and integrated systems for traffic detection and measurement especially fully automatically enforcement.

To measure and control the traffic flow, four video systems mounted on 2 gantries (four lanes each) and different traffic sensors will be installed in the future. Communication from the roadside to the control center will be based on fiber optic cables (FOC) and will achieve high transmission rates for data and video. The test site and its installations can be used and extended in the future easily with new sensor systems for over load, over speed and tolling including different relevant sensor technologies (examples). The focus of these new added sensors will be on technologies for enforcement, its integration and synergy possibilities.

The measurement route is equipped with different sensors (e.g., induction loops, image processing sensors, infrared cameras, in future with WIM, registration for enforcement and possibly tolling) for traffic data acquisition and data fusion, partially installed on two traffic sign bridges. The sensors are primarily set up for the continual and standardized collection of traffic base-load data and field data. The sensors can also be individually configured for the tracking of particular vehicle types, as required.

7. Basic Traffic and WIM Tests

The proposed layout of the WIM area is illustrated in Figure 7. The initial basic test plan consists of the following elements:

- Accuracy test of IM WIM sensor and systems with calibrated vehicles
- Accuracy test with random traffic vehicles and long term stability tests
- ICOM (Installation, calibration, operation and maintenance) tests

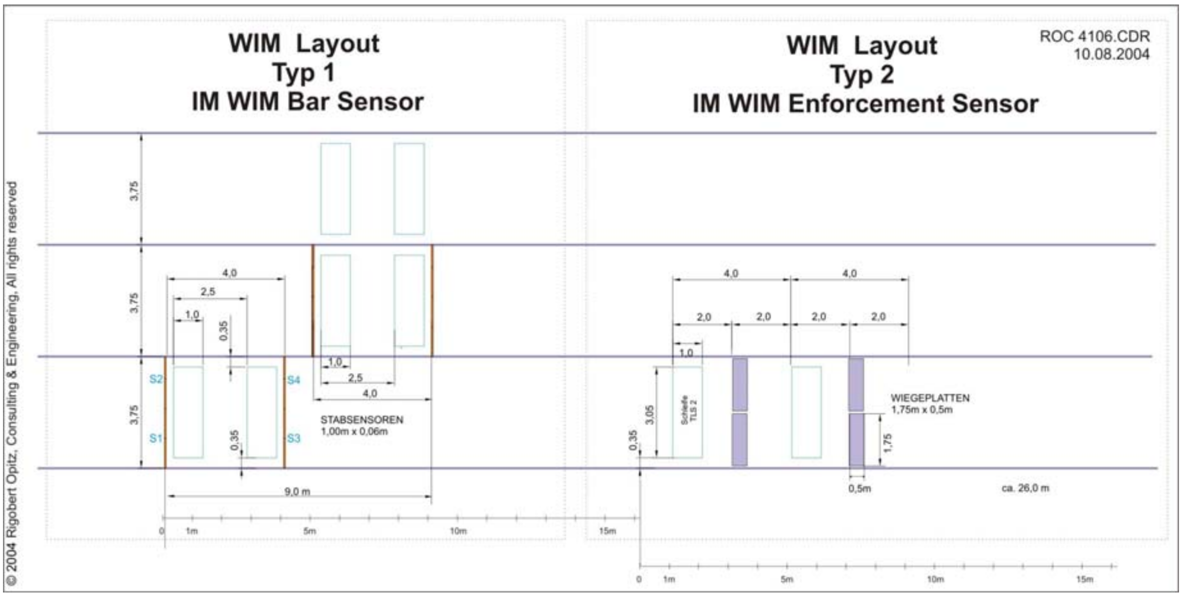

Figure 7 – DLR Berlin Measurement Site: WIM Area

The integration and interfacing of WIM with other traffic sensor and roadside registration systems for multi purpose applications will be included in the second part of tests:

- Interfacing WIM with video registration, vehicle classification systems and tolling
- Tests “Transportkraft” as new physical dimension
- New parameter and input set for pavement deterioration models

- Integrated traffic management, control strategies and VAS Value Added Services.

8. Transportkraft (a New Traffic Variable Including Weight Aspects)

An example of the test programs planned are the investigations concerning the "Transportkraft" (Franke and Brannolte, 2000). Current problems of representing traffic flow conditions and their dynamics initiated a very interesting approach: the idea of the "Transportkraft" (transportforce) as a new physical dimension and innovation for representing traffic more realistically including the "load flow" of heavy trucks.

Instead of using only an one-dimensional traffic measurement magnitude as traffic intensity q [vehicle number/time unit] asusually used applied in many traffic management systems, an extra measurement magnitude with the dimension of vehicle weight [tons/time unit] and the speed over the measuring interval of vehicle[km/h] are included:

$$p_{v[kN]} = \frac{G_{[t]} \cdot v_{[m/s]}}{t_{b[s]}} = \frac{G_{[t]} \cdot x_{[m]}}{t_{b[s]} \cdot t_{[s]}} [N/FZ] \qquad p_{T[N/h]} = \sum_{t=0}^{t=3600} p_{v,i[N/FZ]} \quad t[s] \qquad \text{[N/h]} \qquad (1)$$

where the parameters of this equation are given in Table 1.

Table 1 – "Transportkraft" equation and parameters

$p_{v[kN]}$	"Transportkraft"/Transport force contribution per vehicle	$p_{T[N/h]}$	"Transportkraft"/Transport force per hour
$G_{[t]}$	Vehicle weight		
$v_{[m/s]}$	Instantaneous speed	$t_{b[s]}$	Instantaneous gross time-gap
$x_{[m]}$	Distance	$t_{[s]}$	Time

Such magnitudes will be named transport force, because according to the dimension equation [t*m/s^2] it is physically a force, measured in Newtons. However, it is different from the physical dynamic force.

Their dimension is complied with in the physics recognized in the Fick´s law (Fick, 1855) describing continuous transport phenomena. A modification of Fick´s law was suggested for the discontinuous road traffic.

This modification includes a so-called "Transport-force-contribution" defined for each vehicle; related to the front-vehicle from the product of weight*speed, divided by the gross-time-gap. Based on traffic measurements on a highway (including vehicle weight data), a comparison of daily traffic diagrams separated by cars (PKW) and trucks (LKW) between the classical measuring magnitude (traffic intensity q in diagram 1, called fundamental diagram) and the new approach (using the Transportforce equation in diagram 2) is be given below in Figure 8:

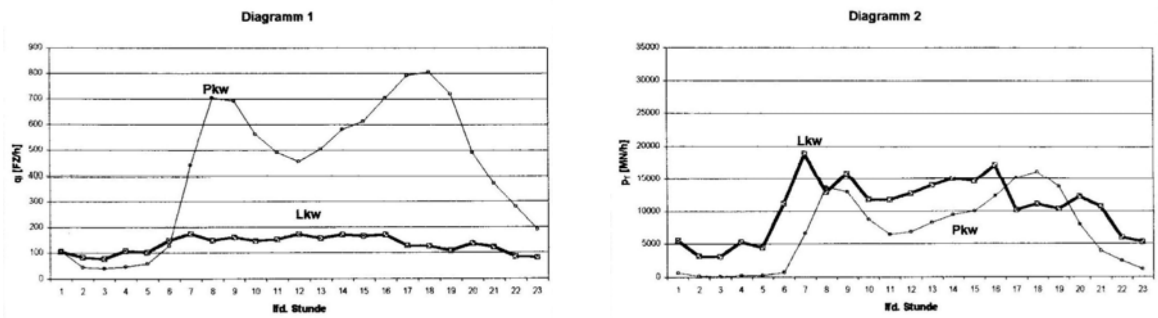

Figure 8 – Fundamental Diagram 1(Left Side) versus Transportkraft Diagram 2 (Right Side)

The X-axis in both diagrams is scaled in 24 hours/day. The Y-axis in diagram 1 represents the "classic" traffic intensity q as used in many traffic control algorithms. In diagram 2 the transport force per hour $\mathbf{p}_{T\,[N/h]}$ is calculated according the Transportkraft equation showing a much higher impact of the truck (LKW) traffic.

The daily diagram 2 using Transportforce correlates better than the quantitative vehicle measurement traffic intensity q with the real traffic load and the observed wear of road underground.

The use of measurement-magnitude Transportforce will lead to more significant parameters and better decisions in the traffic planning and traffic control systems as well as in the analysis of road wear. Such an approach offers more possibilities for future investigations and research compared with the simply quantitative consideration of traffic-intensity.

9. Conclusion

A new precise and reliable WIM sensor and system technology is under development and will allow obviously future "Fully Automatic Enforcement Systems" for truck overload. Modular mini force sensors (Integrated Matrix WIM Sensor) based on strain gauge technology combined with "digital in sensor signal processing" show interesting first accurate measurement results.

Long term stability, higher precision and a new data quality including additional parameters (tire foot print, pressure distribution, lateral wheel position, axle width) will become important features for a new generation of pavement deterioration models with better wear and tear calculation and fully automatic overload enforcement systems.

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PIEZOELECTRIC SENSORS FOR WEIGH-IN-MOTION SYSTEMS : SENSOR BEHAVIOUR ANALYSIS AND RECOMMENDATIONS




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Abstract

Various problems were observed with WIM piezoceramic strip sensors installed on pavement, particularly on motorway 31 in Eastern France, where a multiple-sensor WIM array never reached the expected accuracy. Traffic observation in this area led to assume a significant influence of the vehicles transverse location on sensor response. Thus, this paper presents the results obtained using a 'sensor + pavement' finite element modelling and laboratory and in situ experimentation. Piezoceramic sensors were proved to response to bending load effect. Recommendations for WIM users and manufacturers including a correction law with respect to the transverse wheel location to be applied on WIM measurements are proposed.

Keywords : WIM, Piezoceramic, Strip Sensors, Modelling, Recommendation.

Résumé

Plusieurs problèmes ont été observés avec des capteurs piézocéramiques de pesage en marche installés sur routes, et particulièrement sur l'autoroute A31 dans l'est de la France, où une grille multicapteur n'a jamais permis d'atteindre la précision attendue. L'observation du trafic dans cette zone a conduit à supposer que la position transversale des véhicules avait une influence significative sur la réponse des capteurs. Cet article présente les résultats obtenus à l'aide d'un modèle par éléments finis du système 'capteur + chaussée' et d'expérimentations sur site et en laboratoire. Il est démontré que les capteurs répondent principalement en flexion longitudinale. Des recommandations pour les utilisateurs et les fabricants de systèmes de pesage en marche sont proposées, incluant une loi de correction en fonction du point d'application de la charge pour les mesures de pesage.

Mots-clés: Pesage en Marche, Piézoélectrique, Piézocéramique, Barreau, Modélisation, Recommandation.

動態地磅系統之壓電感測器之行為分析與建議

摘要：

壓電陶瓷棒式 (piezoceramic) 之動態地磅 (Weigh-in-Motion, WIM) 感測器常在使用中發生許多問題；如裝置在法國東部 31 號道路的多重式動態地磅感應器一直無法達到預期的精確度。根據對於此處交通量的觀察可知車輛的橫向位置對感測器的反應造成相當大的影響。因此本研究提出了一個同時考量感應器及鋪面之有限元素模型，並於實驗室及現地進行試驗。結果顯示壓電陶瓷棒式感測器的確能夠反應撓曲載重效果。本文將針對動態地磅使用者與製造者提出建議，內容包含如何在動態地磅量測時針對車輪之側向位置進行校估。

關鍵字：動態地磅、壓電陶瓷棒、條式感測器、模式、建議

1. Introduction

Since the French national 'Weighing-in-Motion' project (1988-92) closure (MELTE-LCPC, 1991; Jacob, 1996), France accumulated a ten years experience on Weigh-In-Motion (WIM) sensors use, laying, and pathologies from a national survey of the WIM station network on highways, SIREDO (Rambeau et al., 1998), and from experimentation on National Road 10 in Trappes (Jacob et al., 1997), on Motorway 31 in Metz (Stanczyk et al., 1999), and within European projects (COST 323, 2002).

Performance requirements and recommendation for installation of WIM systems were defined in (METT-LCPC, 1993) and COST 323 European Specifications (COST 323, 1999). WIM systems performances were evaluated by testing within this COST323 action, but there was still a need for a synthesis of the acquired knowledge on piezoceramic sensor behaviour.

While MS-WIM systems aim at reaching enforcement requirements, a better understanding of sensor behaviour was assumed to be necessary before any further research tending to improve static weight estimation accuracy improvement.

Moreover, various problems were noted with WIM piezoceramic sensors installed on pavement, which led to assume a significant influence of the vehicles transverse location on sensor response. A multiple-sensor WIM array installed on Motorway 31 (near Metz) within the WAVE project (WAVE, 2002) never reached the expected accuracy, because of variations of the traffic transverse location within the lane, suspected to induce scattering of the results. In the mid-90's, some problems were reported to the COST323 Management Committee by R. Henny (DWW) in the Netherlands with piezoceramic sensor accuracy affected by wheels passing close to the sensor edge.

Therefore, before installing a new multiple-sensor WIM array, detailed investigations were carried out on piezoceramic sensor behaviour, using two sensors samples, above all to check their responses close to the edges.

Thus, a 'sensor + pavement' finite element modelling as well as laboratory and in situ experimentation were carried out. Main results reported in (Iaquinta et al., 2004) are summarised here. This paper proposes further investigations.

Laboratory results were used to simulate the effects of an axle passing over the sensor, and led to propose a correction law to be applied to WIM measurements according to the wheel transverse location.

2. Preliminary Results

The two tested strip sensors use the same piezoceramic coaxial cable (®*Vibracoax*) manufactured by the French company Thermocoax.

The first tested bar is composed of this coaxial cable, embedded by Transfibre in several layers of glass fibre mats, injected with epoxy resin (Violette and Fillastre, 1995) to cut non vertical solicitations. This sensor will be named 'Sensor I' hereafter.

The second piezoceramic bar was manufactured by ECM (Electronique Contrôle Mesure), under the licence of and according to the LCPC patent (Etat français - MULT/LCPC, Procédé de mesure des charges dynamiques appliquées à une chaussée par le trafic routier, Brevet d'invention n°85/00101 du 4/1/1985). The same coaxial cable is embedded within a U-shape

metallic beam filled of sand-epoxy mix with low modulus rubber strips on its sides (also to cut non vertical solicitations). This sensor will be named ‘Sensor II’ hereafter.
Two sensors of each type were tested to check the repeatability.

A finite element modelling of a bar in the pavement led to assume that the sensor response would not be only induced by crushing strains as it was usually admitted in the past, but was mainly affected by bending moment strains. This phenomenon could explain some lower response if the load is applied close to the sensor edge, as suspected during some field tests.
A laboratory experimentation was carried out in order to validate this assumption. The sensors were embedded within a metallic frame, representing the groove usually done in the pavement to install the sensors, and with the same dimension, filled with a common acrylic material, similarly to the on site mounting process (Figures 9(a) and (b)). Using a servo-hydraulic jack controlled in force coupled with steel reinforced elastomer block, sinusoidal excitations were produced at different locations distributed all along the sensors.
First, an experimentation was carried out to compare sensor response to bending and to crushing. The sensors output signal was shown to be 70% higher for bending solicitation than for crushing solicitation. Comparison of laboratory results and finite element modelling was performed (Figure 9(c)). Simulation was proved to be realistic for each location of the applied force.

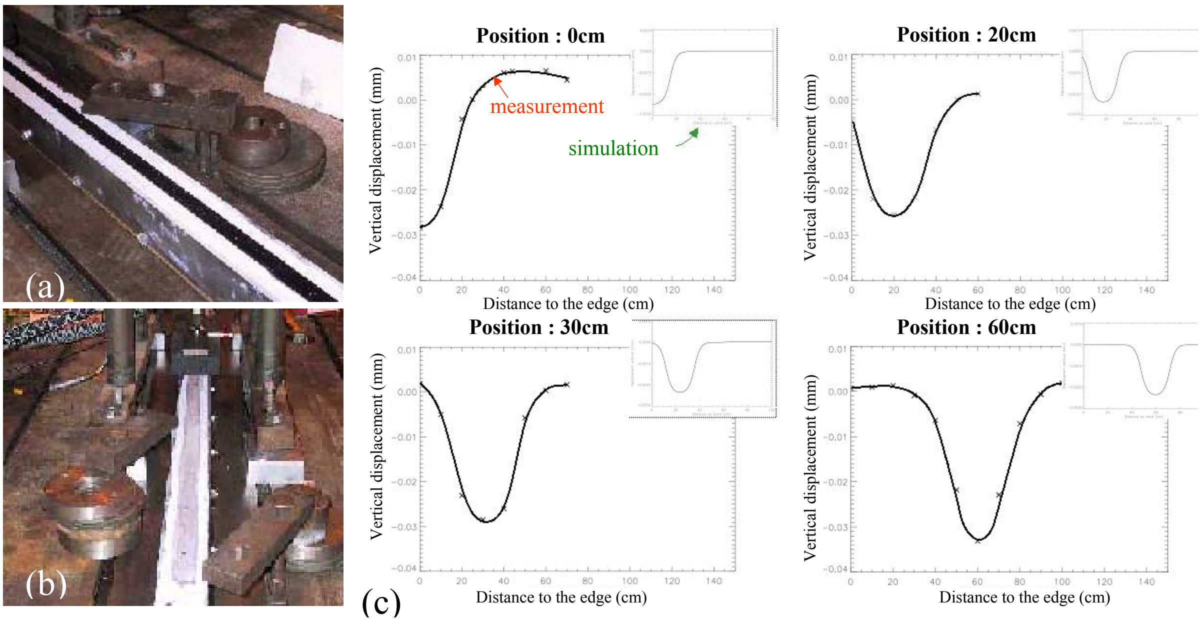


Figure 9 – (a) and (b) Pictures of the Bar within the Frame during Laboratory Trial;
(c) Vertical Displacement According to the Applied Force Location close to the Sensor Edge (0 - 0.6m) – Comparison of Simulated and Real Behaviour (Iaquinta et al., 2004)

The electrical response of Sensor I and Sensor II with respect to the location of the force application was recorded with a charge amplifier. Force location varied from 0 to 1.65m with respect to the edge. Figure 2 shows the results for applied pressures of 740 kN/m², which is close to the pressure under a heavy truck wheel tire. The electrical response was normalised with respect to the maximum value reached in the middle of the bar. Figure 2 was constructed by assuming that sensor behaviour was symmetrical.

The sensor response varies along the sensor length from 75% (Sensor I) or 70% (Sensor II) up to 100% of the central maximum response. From the bending/crushing measured ratio and from Figure 1(c), it is derived that on the edge, response is the sum of 50% due to local bending, plus 20% due to crushing. Crushing strains are constant all along the sensor, but bending strains are increasing from 0 to app. 50cm with respect to the edge (Figure 1(c)). This phenomenon explains the linear increase of Sensor II response from 70 to 90%.

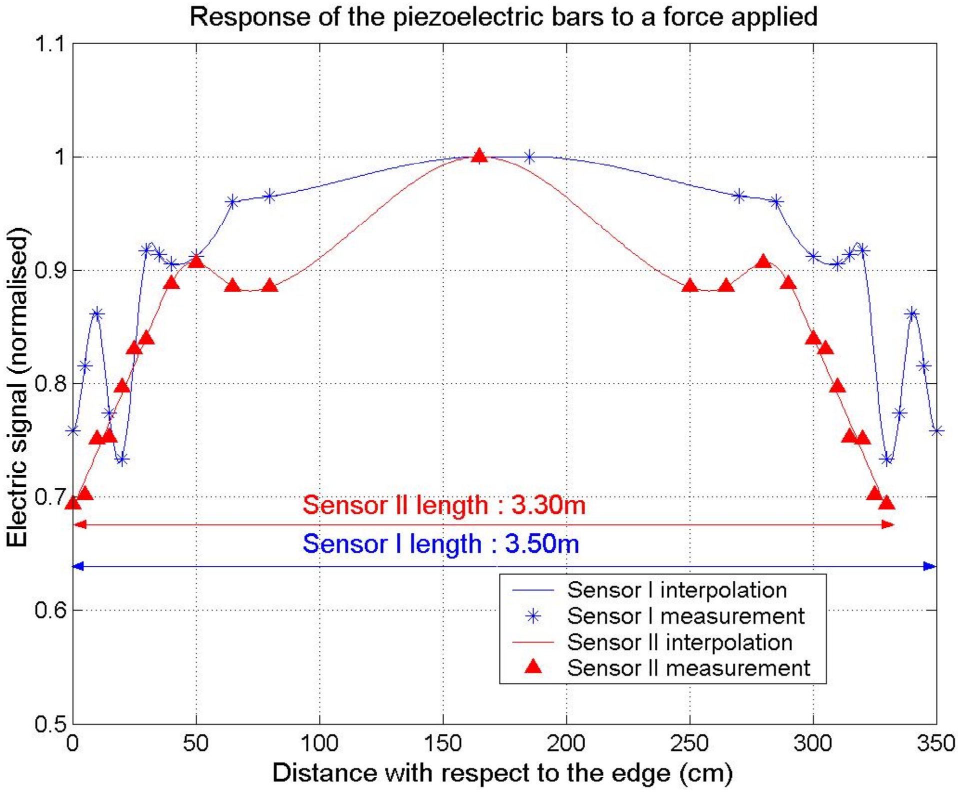


Figure 2 – Response of the Piezoceramic Sensors to a Pressure Applied at Several Locations Along the Bar.

The behaviour of the Sensor I in this area is more unpredictable, likely affected by random noise. That may be explained by the difference of stiffness between both Sensors. The Sensor II is stiffer than the Sensor I because of its U-shape metallic beam, which smoothes the local strain variations. Finally, looking at the central area of the sensor (interval [0.5m;L-0.5m] if L is the sensor length in m), it seems that app. 10% of the maximum response results of a general bending moment (affecting at least (L-1)m of the sensor length).

Further studies should be carried out to focus more on sensor behaviour in central area. In this research, as interest was initially granted for sensors edge effects, only a few points were measured in the sensor central area, thus, spline and linear interpolation were performed to plot Figure 2.

Despite of the different behaviours of Sensors I and II, both of them partially loss their sensitivity when the wheel loads are applied close to the edges. Therefore, without any correction, and as recommended by most of the vendors, a 'useless zone' between 0 and 40 to 50 cm (at each side) is defined where the weight can't be accurately measured. That is the reason why it is recommended to use sensors app. 1 m longer than the distance between the extreme right and left wheel paths on the road, and centred on the mean truck longitudinal axis.

However, because the response of Sensor II linearly increases from its edge all along the first 50 cm, measurements could be corrected in the edge area, by using a linear function (of the distance) as a correction factor. In such a case, it may not be necessary to use sensors much longer than the distance between extreme wheel paths.

These results are not fully representative of the response obtained when a whole axle (at least two wheels) is passing over a piezoceramic bar in real conditions of use. An axle induces one force by wheel on the sensor, i.e. two or more forces (case of twin tires). Therefore, a simulation of the sensor response to an axle solicitation was performed.

3. Simulation of the Effect Induced by an Axle

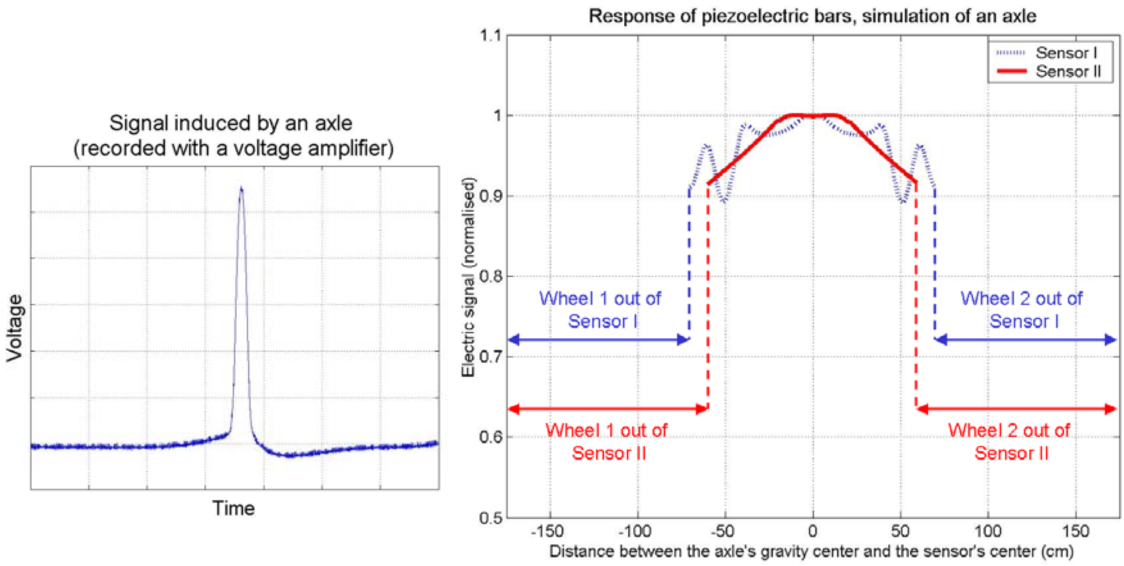
The results of the laboratory trial described in section 2 were used to simulate the effect of an axle, assuming that each wheel applies a force. The sensor response was computed using the superposition principle, i.e. electrical responses due to each simulated wheel were simply added.

Of course, this simulation does not allow to take into account the real force induced by one wheel. Figure 3(a) shows a sensor signal recorded with a charge amplifier, so that the associated axle weight is proportional to the amplitude of the peak. This real signal is the result of both trucks dynamic and road deflexion. During our experimentation, we applied some varying vertical forces, simplified compared to the real wheel force. The sensor response is then also simplified, and so is, by extension, the response to the axle simulation.

Moreover, all the axle wheels are supposed here to induce simultaneously the same force (symmetric truck).

For these reasons, results of this simulation must be taken with care.

Figure 3(b) shows the response calculated when two forces with the same intensity (representing each wheel of an axle) are applied at different transverse locations of the sensor.



(a) (b)

Figure 3 – (a) Real Sensor Output Signal induced by an Axle; (b) Normalised Response of the Piezoceramic Sensors to a Simulated Axle Force

This response was calculated by summing the interpolated values given in Fgiure 2, for two forces applied with a spacing of 2.10m (distance between left and right wheels of an usual axle). The results for each sensor were plotted versus the transverse location of the middle of the axle, within the area where both wheels are on the sensor.

Some loss of accuracy may be induced by the interpolation. More sensor response measurements would be needed, especially in the central area, to perform a more accurate axle simulation.

The two curves are quite similar with those of Figure 2, with some expected differences: (i) the plateau of the central area is reduced to 70 cm in length for Sensor I and 30 cm for Sensor II; (ii) the responses are almost flat along this plateau for both sensors (variations within 2% for Sensor I), and drop down by 10% at the sensor edges; (iii) similar signal variations are shown in the edge zones as with one wheel for each sensor (i.e. erratic variations for Sensor I and linear increase for Sensor II).

The drop down amplitude of the response is divided by 2 when a whole axle passes on the sensor because if the left wheel passes near one sensor edge, the right wheel passes in the central area. This reduced response decrease, which is only app. twice more than the maximum longitudinal scattering expected for such type of WIM sensors (i.e. app. 5%), may explain why the “bending behaviour” phenomenon was not discovered sooner, and did not affect the current and past WIM system too much, which generally are in accuracy classes from C(15) to D(25) according to the COST323 European Specification.

According to the shapes of each response, a 'useless zone' of 30 to 40 cm must be avoided near the edges of the Sensor I, but a linear correction factor could be applied to the Sensor II response which may thus be used in whole.

Without any correction factor, as it is usually the case for most of the marketed WIM systems, vehicles may be mis-weighed (underweighted if the calibration is done for lorries centred in lane) if the distance between their centre of gravity (longitudinal axis) and the sensor edge is less than 1.3 to 1.4 m for Sensor I, and 1.5 m for Sensor II (assuming that the wheel spacing for an axle is approx. 2 m).

With a linear correction factor, and if the transverse location of the wheels is measured, this error may be theoretically avoided for Sensor II, but not for Sensor I.

The interpolated distribution of sensor response to an applied force was also used to simulate the influence of varying distance between left and right wheel (from 1.80m to 2.30m). It was shown that, as expected, the longer the distance between the left and right single tires, the shorter the plateau or the useful zone, whatever the sensor type. Only the useful zone or the plateau length was influenced: no significant effect could be noticed on the response amplitude.

Sensor response to an axle with twin tires was also simulated. Simulated twin wheels did not induce significant change in plateau or useful length, but variations of the response along the sensor was less important (95% to 100% of the maximum value for an axle with twin tires, against 90% to 100% for an axle with single tires).

Results of a 2.10m in width simulated axle were then compared to those of in situ measurements in order to check the validity of these simulations. This is a critical step prior to up-date sensor installation recommendation and best practices for WIM users.

4. Analysis of in Situ Measurements and Correction

Measurements were carried out for the two sensors on existing instrumented sites, in order to assess the effects of wheel transverse location on sensors response.

The test truck used on both test sites was a fully loaded 5-axle articulated vehicle (gross weight: 36 tons) with distances between left and right wheel close to 2.10m (except for the twin wheels of the 2^{nd} axle). 15 runs were planned with different transverse locations and different speeds in extended repeatability conditions (r2) and environmental repeatability (I) according to COST323 specifications. The test site instrumented with Sensor II did not provide enough runs to carry out further analysis (local road geometry was not appropriated for transverse location variations).

Thus the following analysis only concerns Sensor I.

4.1 Comparison with Simulation Results

The distribution of Sensor I response with respect to the transverse location of the truck is represented in Figure 4. The right wheel locations varied from 0.05 m from the edge, outside the lane, to 1.5m from the edge, inside the lane. The comparison with Figure 3(b) allowed to determine five different areas.

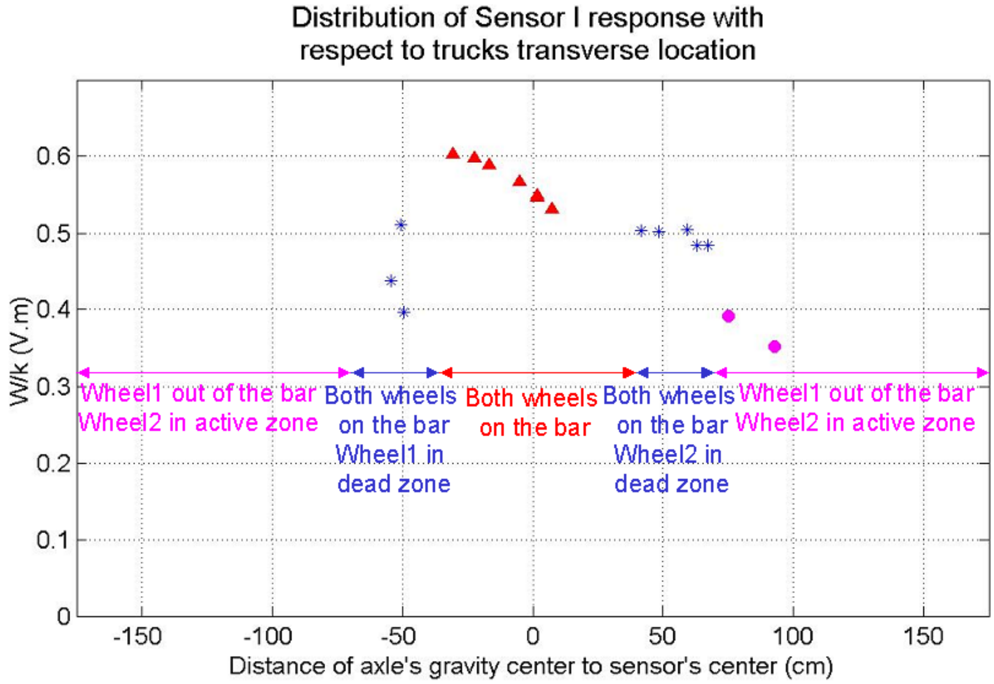


Figure 4 - Distribution of Sensor I Response (Total Weight of the Truck) with Respect to Transverse Location of the Truck on National Road 77 Test Site (Arcy-sur-Aube)

The two external areas (circle marks) correspond to the areas where one wheel is out of the sensor, while the other wheel is on the plateau of the sensor response (useful zone). The measurements correspond to one half of an axle. The response is scattered as expected.

The intermediate area (star marks) represents the part of the sensor where both wheels are located on the sensor but one of them is on the 'useless zone'.

The central part (triangle marks) shows the results for the whole axle centred on the bar. Measurements are slightly scattered (5% variations around the mean value) even if the response was not expected to be related to the distance in this zone. This scattering could be explained by the sensor + pavement system 'natural' scattering or by trucks dynamics, which induces varying impact force from one run to the other.

Those data were recorded as an output of the voltage amplifier, without any electronic treatment of the WIM station. That means that they are not affected by automatic calibration, but that the signal was integrated and multiplied by the speed of the truck in order to obtain a W/k value, which is proportional to the weight.

For the following parts, it will be considered that even if the response is not steady in the useful area, the behaviour of the sensor complies with the results of the simulation. Indeed, the different zones are clearly defined, and the variations in the useful area could be simply due to variations of impact forces applied by the axle on the road.

4.2 Description of the Correction Law

As mentioned previously, a correction law should be considered for Sensor II. The useful zone, where the response does not vary with the location of the applied load, is short, but for the remaining part of the sensor, a linear distribution of the electrical response is shown. The linear distribution equation of the correction curve has probably to be fit with on site test measurement for each experimental site.
Then, the signal can be modelled with a correction curve, as described in Figure 5.

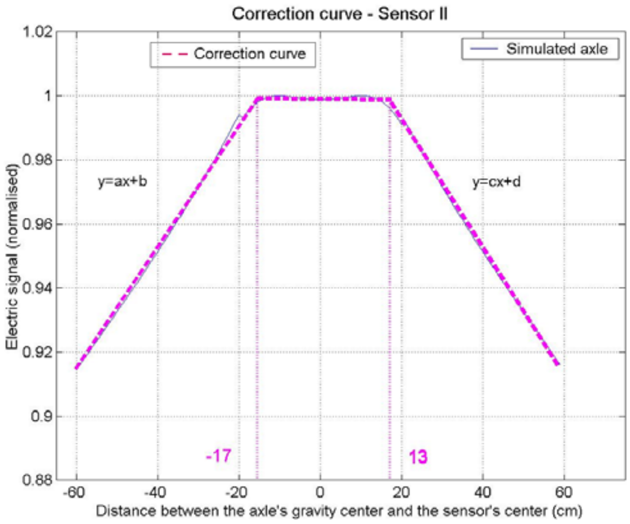


Figure 5 - Modelling of Sensor II Response with respect to Axle's Gravity Centre Location

Because it was shown that no simple and reliable correction can be applied for Sensor I, its response can be considered as correct in the useful zone, and useless for any location outside this zone. Thus, the correction curve is replaced by a "truncation curve" (shown in Figure 6) where the values outside the plateau are eliminated.

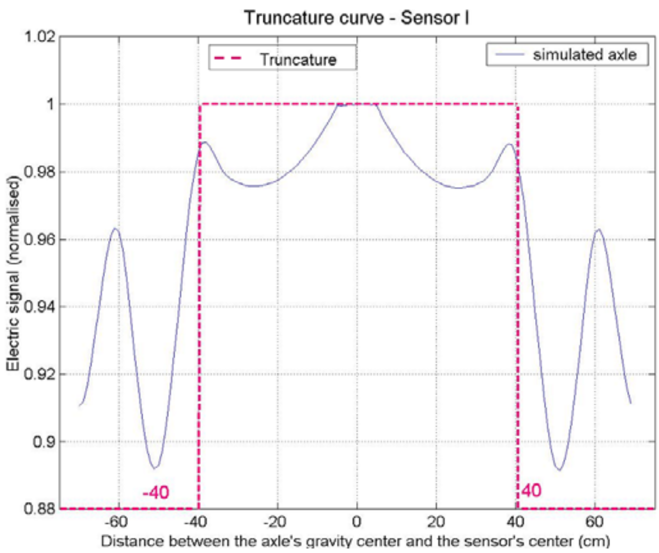


Figure 6 - Modelling of Sensor I Response with Respect to Axle's Gravity Centre Location

4.3 Application of the correction law to real Weigh-In-Motion data

Knowing the lateral position of the axle passing on the sensor, the corrected WIM data is computed by division of the measured WIM data by the correction factor (i.e. the value of the correction law for the measured transverse location).

For Sensor II, as the correction curve was obtained in laboratory, it may slightly differ from the one assessed for a sensor embedded in a pavement. The slope of the curve likely depends on the type of pavement, the rutting, the deflection, the type of resins and the installation condition of the sensors in the pavement. The coefficient of the correction law have to be fitted on site measurements. Moreover, our site tests did not provide enough data to both fit the correction curve and evaluate the corrected data accuracy.

Thus, the results presented afterwards are related to Sensor I. The truncation curve is very simple and is assumed to be independent of the site. This assumption will have to be verified with further experiments.

Two samples were considered: the first sample includes runs with both wheels on the sensor, whatever the transverse location within the sensor. The second sample includes only runs with all the wheels passing on the steady zone; almost a half of the runs were eliminated by truncation. Thus, the sample 1 and 2 sizes are 45 and 24 runs.

The accuracy comparison is then carried out according to the COST 323 Specifications (Tables 1 and 2). These tables show that applying the truncation curve led to reduce the standard deviations by 33%. The accuracy jumped two classes up for all criteria.

Table 1 - COST 323 accuracy, sample 1 (runs with both wheels on Sensor I)

SAMPLE 1	**No.**	**Mean**	**Std. Dev.**	Π_o	**Class**	δ	δ_{min}	Π	**Retained Class**
Criterion		(%)	(%)	(%)		(%)	(%)	(%)	
Single axle	15	-1.80	11.87	92.9	E(30)	30	30.0	92.9	E(35)
Axle of a group	15	-2.43	13.86	92.9	E(35)	38.5	35.1	95.5	
Group of axles	30	-2.98	11.36	95.3	D(25)	30	28.5	96.4	
Gross weight	45	-2.43	13.79	96.1	D(25)	35	33.8	96.7	

Table 2 - COST 323 accuracy, sample 2 (runs with both wheels on Sensor I 'useful zone')

SAMPLE 2	**No.**	**Mean**	**Std. Dev.**	Π_o	**Class**	δ	δ_{min}	Π	**Retained Class**
Criterion		(%)	(%)	(%)		(%)	(%)	(%)	
Single axle	8	2.21	7.60	87.2	D+(20)	20	19.9	87.4	D(25)
Axle of a group	8	2.56	9.04	87.2	D(25)	28	23.7	93.6	
Group of axles	16	-0.71	7.52	93.2	C(15)	20	18.9	94.9	
Gross weight	24	2.56	8.95	94.7	C(15)	25	22.7	96.9	

Of course, sample 1 was a study case, not fully representative of most of the real cases, because the scattering of the test truck transverse location was imposed. This scattering of the runs transverse location led to a significant loss of accuracy.

If only the trucks runs with wheels outside the plateau are considered as a sample, this sample is the difference between sample 1 and sample 2. The corresponding mean and standard deviation of the gross weight error (described here, but the same could be done for the 3 other criteria) can be computed using the raw data or a statistical formula:

$$n=n_1+ n_2 \;,\; m=(n_1m_1+ n_2m_2) /n \;,\; s^2 = (n_1s_1^2+n_2s_2^2)/n + [n_1(m_1-m)^2 + n_2(m_2-m)^2]/n \qquad (1)$$

where n, m and s are the sample size, mean and std. dev., the indices being 1 for sample 1-sample 2, 2 for sample 2, and the result for sample 1.

Here, a back calculation (knowing n_2, m_2, s_2, n, m, s) gives m_1=–8,13% and s_1=16%. Moreover, if the calibration of the WIM system is done using the "good sample" (sample 2), the mean bias of this sample m_2 should be removed ($m_2 \approx 0$), which would lead to skip all the results 2.5% lower. In such a case, the mean error of the whole population (sample 1) would be –5%, and the mean error of the badly weighed trucks (sample 1-sample 2) would be as low as –10,6%. This confirms that the weight are underestimated by down to -10% when one wheel passes on the sensor edge. Simultaneously the error standard deviation highly increases because of the quick variation of the sensor response, here up to 16%, almost twice more than for the trucks passing well on the sensor.

These results also confirm a phenomenon already observed during past experiments and European trials, and above all the Cold Environment Test (COST323, 2002; WAVE, 2002).

5. Recommendations and Conclusions

As predicted by recent finite element modelling, the piezoceramic WIM sensors embedded in epoxy bars, whatever the design method, i.e. with or without a U-shape metallic beam, were shown to respond not only to crushing strains, but mainly to bending moment strains. A laboratory trial allowed to confirm this phenomenon and to rather accurately quantify the sensor response with respect to the longitudinal abscissa of the applied force (pressure). 80% of the maximum response intensity comes from the bending effect (local or general effect), while the remaining strains are induced by crushing.

This sensor behaviour, newly pointed out, mainly explains some problems already encountered by WIM users in the past decade, i.e. a loss of sensitivity close to the sensor edge, which affects the system accuracy, and, if used, the automatic self calibration results.

For the two models of sensors available on the market (in France at least), it was shown that along the last 50 cm at the sensor edges, app. 20% of the response is lost, either with a linear decrease for the LCPC's patented sensor (Sensor II, embedded in a metallic beam), or with erratic variations for the "Transfibre" sensor (Sensor I, embedded in a glass fibre reinforced epoxy bar).

In the sensor central area, the response slightly increases (by 10%) to reach its maximum at the middle of the sensor. This behaviour was explained by the bending moment effect superimposed to the crushing and local bending effect.

The sensor behaviour under an axle (i.e. two wheels or two pairs of twin wheels) was also simulated, and the same phenomena were found, but the loss of response at the sensor edge was divided by two, because only one half of the axle was in the edge area. It means than the loss of response is less than 10%, which may explains why this phenomenon was hidden until now in the experimentations, and generally did not too much affect the accuracy of WIM systems, for classes C(15) and lower. However, for enforcement purposes, it becomes necessary to improve the accuracy of WIM, and therefore it was important to try to handle this issue.

A site test was carried out with one of the two sensors, which mainly confirmed the previous findings. The proposed truncation law led to a 33% standard deviation reduction for all criteria. A correction law (linear factor with respect to the lateral wheel location) was also proposed to correct the response of the Sensor II. If applied, the sensor may be used all over its length. Otherwise, a 'dead zone' must be taken into account at both edges, such as for the Sensor I which shows an erratic response in this zone, and the trucks with a wheel passing on this zone must be identified and rejected (use of an "off-scale" sensor).

The recommendations for WIM sensor installation (either issued by vendors or others), as well as the COST 323 specification should be completed in order to avoid the described problems (loss of accuracy) and to take into account the results of this investigation, above all for highly accurate WIM systems. However, before doing that, it is recommended to carry out some more site trials, including accurate wheel path location measurements, and to deeper analyse their results. Some exchanges with the sensor and WIM software manufacturers will also be useful to implement these findings.

When choosing a new WIM site, it is necessary to check the transverse location distribution of the truck path within the traffic lane, using for example a video system. Either the sensor length and location must be chosen according to the previous results, or, if the wheel paths are too much scattered, the site might be rejected.

These results will have to be completed by in situ larger scale experimentations and some complementary laboratory trials might be useful to determine more accurately the sensor behaviour in the central area of the sensors. Our investigation was carried out for semi-rigid bituminous pavements. In case of concrete rigid pavements, it is expected that the influence of the wheel transverse location on sensors response would be weaker because of the negligible bending phenomenon.

Acknowledgements
This study was carried out by a team of the Metrology and Instrumentation Service of LCPC, composed of Jean Iaquinta, Jean-Marie Caussignac, Louis-Marie Cottineau, Jean-Pierre Desroche, Erick Merliot, Michel Nobili, and the authors.

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NOTHING-ON-THE-ROAD AXLE DETECTION WITH THRESHOLD ANALYSIS

  

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Abstract
As any other weigh-in-motion system, the bridge WIM requires information about axle spacings to successfully calculate the axle loads. On some bridges this axle spacing information can be obtained from the strain signals measured at specific locations under the bridge rather than from the conventional axle detectors. After the first successful attempts of a Free-of-Axle Detector bridge WIM system at the end of last century, further developments were needed before such procedure, also known as NOR (Nothing-On-the-Road), could have been used for real long-term measurements. The paper describes the method which first cross-correlates the measured strain signals from two different longitudinal positions to obtain accurate estimate of its velocity. Then they are processed and optimised to define the exact number and spacings of the axles. Efficiency of this robust method is illustrated with results from a short span slab bridge and a longer beam-deck bridge. Successful implementation of the new improved algorithm resulted in almost 50% of all WIM installations in Slovenia (around 20 bridges every year) being of the NOR type.

Keywords: WIM, Weigh In Motion, Bridge, NOR (Nothing On the Road), FAD.

Résumé
Comme n’importe quel système de pesage en marche, le système de pesage par pont instrumenté nécessite des informations sur les distances inter-essieux afin de calculer les charges d'essieux. Sur certains ponts, les distances inter-essieux peuvent être obtenues à partir des signaux de contrainte mesurés à des endroits spécifiques sous le pont plutôt qu'à partir de détecteurs courants de passages d’essieux. Après des premiers essais satisfaisant d’un système de pesage sans détecteur d’essieux sur la chaussée (FAD), réalisés à la fin du siècle dernier, des développements supplémentaires étaient nécessaires avant qu'une tel système, également connue sous le nom de NOR (Nothing-On-the-Road - rien sur la chaussée), puisse être utilisé pour réaliser des mesures réelles de pesées sur de longue période. L'article décrit la méthode qui tout d’abord cherche une intercorrélation entre les signaux de contrainte mesurés à deux positions longitudinales différentes, ce qui permet d’obtenir une évaluation précise de la vitesse. Ensuite, ces signaux sont traités et optimisés afin de mesurer le nombre et les distances inter-essieux. L'efficacité de cette méthode robuste est illustrée avec des résultats d'un pont dalle à courte portée et d'un pont à poutre plus long. Le succès de l’implémentation du nouvel algorithme NOR a eu pour conséquence de l’installer sur 50% des ponts instrumentés en Slovénie (autour 20 ponts).

Mots-clés: Pesage en Marche, Pont, NOR, FAD.

NOTHING-ON-THE-ROAD 之軸重偵測以及門檻值分析

摘要：
如同其他形式之動態地磅系統 (Weigh-in-Motion, WIM) 一般，橋梁動態地磅需要軸距之相關訊息以成功進行軸重之計算。在某些橋梁上軸距資料係採用埋設於橋梁底特定位置之應變計量測得之而非經由傳統軸重偵測獲得。因二十世紀末對於 Free-of-Axle Detector (FAD) (無軸偵測器)橋梁動態地磅系統之成功嘗試，這個系統(常被稱爲 Nothing-On-the-Road, NOR) 需要更進一步之發展以進行長期監測。本文描述利用兩個不同縱向位置所量得之應變訊號進行交互相關分析以獲得正確預測速度之方法，而後進行資料處理以及最佳化以定義輪軸之數量以及間距。此一方法之效率係利用由短跨距剛性混凝土版塊橋以及較長之梁版橋所得之資料進行探討。此一演算法之成功驗證使得斯洛維尼亞半數以上之動態地磅採用 NOR 之方式安裝。

關鍵字：動態地磅、橋梁、NOR、FAD

1. Introduction

The need for knowing real traffic loading is essential for efficient road maintenance. This data can be obtained with different WIM (Weigh-in-Motion) systems, either being of pavement or bridge type. While the pavement systems use weighing sensors installed into the pavement, the bridge WIM (B-WIM) system uses instrumented and calibrated bridge superstructures that act as weighing scales (Moses 1979, Žnidarič et. all 1999 and 2002). B-WIM was extensively studied in mid 1990's in two European projects: the COST 323 action "Weigh-in-Motion of Road Vehicles" and especially in the Work Package 1.2 of the European 4th Framework research project "WAVE – Weighing of Axles and Vehicles for Europe" (WAVE 2001). Since then research continued individually in several countries around the world. In Slovenia, the prototype SiWIM system from WAVE evolved into a standalone product which is constantly improved and upgraded.

Until recently all WIM systems required special sensors for detecting axles of the vehicles and consequently, for calculation of their velocity. This data is also needed to classify vehicles and to calculate their axle loads and gross weight.

2. Axle Detection in WIM Systems

Number of axles, axle spacings and velocity of a vehicle are the required information when calculating axle loads with any WIM system. For this purpose, at least two sensors are needed at the known distance in each driving lane. Axle detectors can be used either exclusively for detection of axles or are performing this job as a part of weighing procedure. The common types of axle detectors are inductive loops, pneumatic hoses, tape switches, fibre optic sensor or even less accurate weighing sensor, such as piezo-ceramic bars. The main disadvantage of all axle detectors, especially those for permanent setups, is the installation and maintenance procedures, which cause considerable traffic delays. Sensors also deteriorate over time.

A major advantage of bridge WIM is its portability, i.e. its feature that the entire system can be moved quickly from one site to another to collect representative samples of traffic data during short-term, 1 to 2 week measurements. In such cases also the axle detectors can be exchangeable, with rubber hoses stretched across the pavement being the most popular selection (Figure 1, left). They are cheap and efficient and provide, with appropriate signal conditioning, sharp peaks for individual axles. The first generation of bridge WIM systems used mechanical tape switches (Figure 1, right), but they have proved unreliable and more difficult to install. A promising alternative are the axle detectors based on optic-fibre technology, but they have not been tested with a bridge WIM system yet.

To eliminate all actions on the pavement and, consequently, to improve durability of WIM systems, to decrease costs of installation and to reduce inconvenience to the road users, the WAVE project introduced FAD, the Free-of-Axle Detector bridge WIM which processes the required axle information from the measured strain recordings. First successful demonstrations were made on orthotropic deck bridges (WAVE 2001) and on short slab bridges (Žnidarič et all, 2002). Yet, to be reliable under any road, bridge and traffic conditions, the FAD, also known as NOR (Nothing On the Road) bridge WIM systems required substantial further developments.

Figure 1 – Axle Detectors: Pneumatic Tubes (left), Tape Switches (right)

3. Types of Bridges Used in NOR

In a NOR B-WIM system information from conventional axle detectors is replaced by the signals from the strain transducers attached to the bottom side of the bridge superstructure. These transducers can be either those already used for weighing or some additional ones placed in locations where sharp axle peaks can be recorded (WAVE, 2001).

Not all bridges are suitable for NOR installations. As the bridge span length is practically always longer than the short axle spacings, the measured strain signals always represent joint contributions of several axles that are on the bridge at the time. More axles on the bridge, more difficult it is to identify the axle spacings. Thus, the ideal NOR bridges are either short or have secondary elements that divide the main span into short "sub-spans", such as cross-beams or cross-stiffeners (see the examples below). Thicker superstructures smear the individual peaks in the signal, which makes axle identification more difficult.

WAVE project started to develop the NOR algorithms on the orthotropic deck bridges, which have very thin steel deck and cross-stiffeners at every 3-5 meters. This is ideal for NOR as individual axles are clearly seen in the signal and rather simple algorithms can identify axles from the strain signals. Yet, as these bridges are scarce, other "less-ideal" bridges had to be investigated to raise the practical value of the method. WAVE therefore suggested to install NOR on 6 to 10 meter long slab bridges, with as thin slabs as possible (usually 0,5 to 0,8 m thick). If pavement was smooth (there was no bump on the approach to the bridge), encouraging results were obtained, with most of the axles identified (Žnidarič, 2002). However, a universal algorithm that would work on most "real life" structures, with correct identifications success rate of 99% and above, required a considerably more robust algorithm.

3.1 Sample Strain Signals

Figure 2 demonstrates appropriateness of different types of bridges for NOR. Each example is illustrated with a photo and a typical response of the structure during a passage of a conventional fully loaded (40 tonnes) 5-axle semi-trailer, with 2 single and a triple axle.

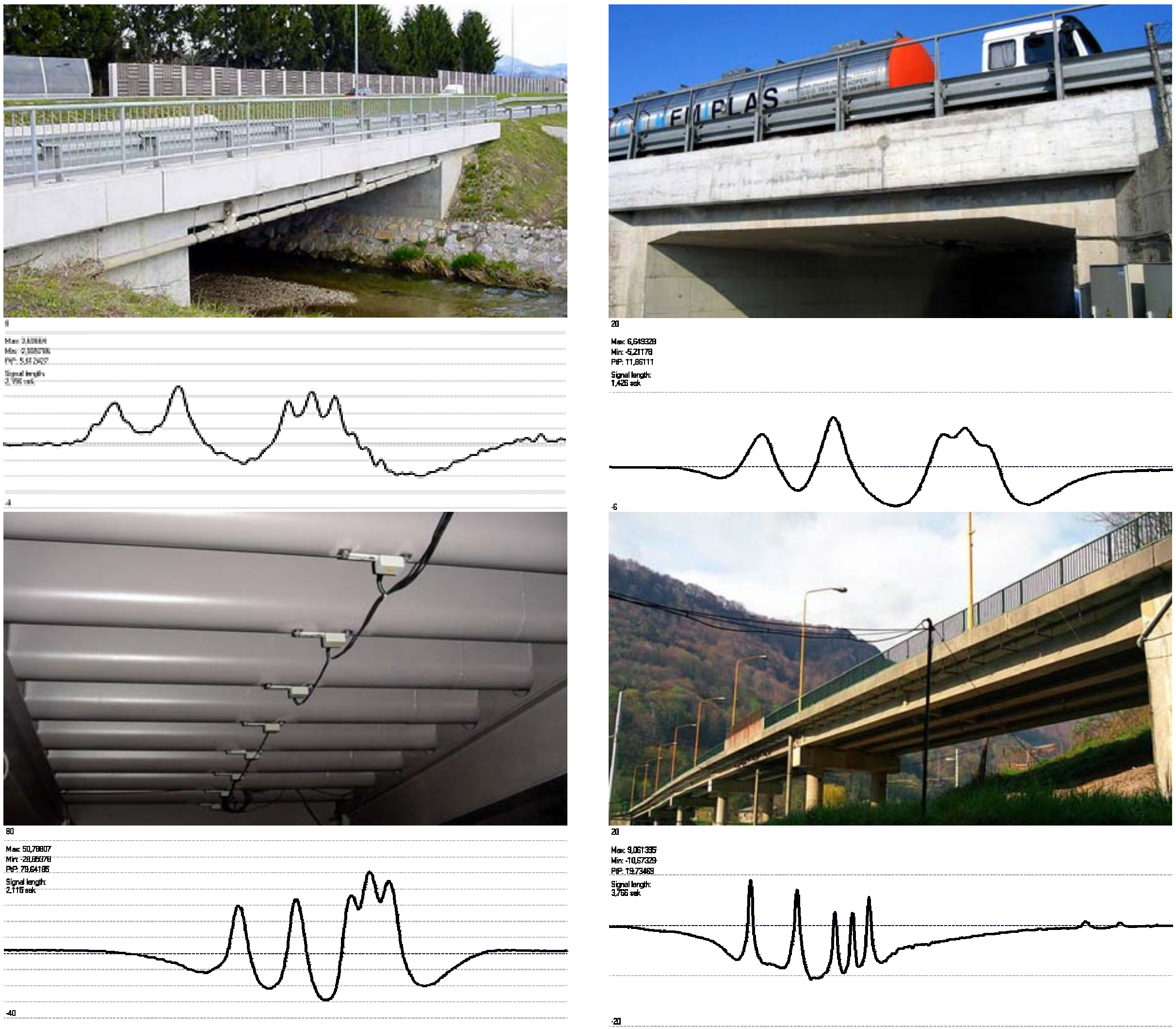

Figure 2 – Clock-wise: Bridge with High Dynamics, Bridge with 0.8 m Thick Slab, Orthotropic-Deck Bridge, Beam-Deck Bridge Instrumented on the Slab between the Beams

1. If the bridge is thin and longer and its eigen-frequencies match those of heavy vehicles or there is a bump on the road just before or on the bridge, the pronounced dynamics of the vehicle-bridge interaction imposes additional peaks into the signal, often with a frequency that is in the range of shorter axle spacings. If and to what extent they appear depends on characteristics of the vehicle, its weight and speed. Such peaks must be ignored and not treated as axles. The top-left example shows response of a fully loaded 5-axle semi trailer over a 12 m long and 0,5 m thick slab bridge.
2. If bridge superstructure is stiff and smooth, as was the 6-m long integral bridge with an 80 cm thick slab (top-right), there will likely be no dynamics, but peaks from individual axles, especially axles from a group, can be smeared and difficult to find. Here, the peaks are far less apparent also because sensors were installed closer to the midspan than in the first case, where they were mounted at the quarter spans.

3. WAVE already identified the orthotropic deck bridges (bottom-left) as suitable for NOR installations. Indeed, results from a bridge near Warsaw in Poland, which was instrumented for a week in the scope of the European Commission 5th Framework project SAMARIS (Žnidarič et all, 2004), confirmed, that this can be done without any major constraints. The bridge had 6 spans with total length of over 500 m. The strain transducers were installed on the deck stiffeners laying on the transverse cross-beams spaced 2,5 m apart from each other. Position close to the first pier was used to reduce the effects of global deflections of the measured span.
4. The recent research and tests confirmed that, with some restrictions, NOR can also be used on longer beam-deck bridges, as was the one with six 30,5 m long simply supported spans (bottom-right). The strain transducers for detecting axles were attached to the slab between two beams, close to the cross-stiffener at the mid-span. It is interesting to observe that the individual peaks are even sharper than those measured on the orthotropic deck bridge.

From the diversity of shapes of the strain signals it is evident that developing an algorithm that would identify the majority of axles under all conditions on all types of possible NOR bridges was a challenging endeavour.

4. SiWIM System and NOR

The SiWIM was introduced during the WAVE project which as one of its deliverables produced a software prototype of a bridge WIM system. Since then the SiWIM has undergone significant changes. The first 2 versions, developed between 1999 and 2002, mainly improved the hardware, reliability of the basic bridge WIM algorithm and user-friendliness of the software. Subsequently, the main efforts in the last 2 years were oriented towards:

- extension of its application to bridges not being recommended by WAVE yet, such as beam-deck bridges over 20 m in length,
- development and implementation of the NOR measurements and
- increasing number of successful weighing on less ideal bridges by implementing recursive methods which in an 'intelligent way' correct errors due to bad measurements (i.e. as a result of bridge-vehicle dynamics, multiple presence of many vehicles on the bridge, errors of axle detectors etc.).

4.1 Advanced NOR Algorithm

As stated above, the main challenge in the area of NOR was to increase number of successful vehicle identifications (correct axle spacings), especially on the less appropriate structures.

The first step in a NOR algorithm is to define the vehicle velocity. The WAVE project proposed to calculate it from the time difference of peaks from the strain signal (WAVE, 2001). This gave satisfactory results on "ideal" bridges that generated sharp strain peaks under the axles (Figure 3) but caused major problems on the less ideal bridges with pronounced dynamics (with too many peaks) or with longer and thicker superstructures (with smeared peaks), such as the 2 examples in the top row of the Figure 2. Calculation of a correlation function has shown to give more robust results. The applied algorithm correlates strain signals recorded at two different longitudinal positions, in times τ and $(\tau+t)$, using the following function:

$$Corr(g,h) = \int_{-\infty}^{\infty} g(\tau + t)\, h(\tau)\ d\tau \tag{1}$$

Even if shapes of both signals do not entirely match, the maximum value of the function corresponds to the time difference between the two measured signals. To make contributions of different vehicles in the same signal independent of velocity, the signals are first converted into the space domain.

Appropriate filtering is crucial if signals are affected by dynamics or when axles from the groups are heavily smeared, as on the bridge with the thick slab in Figure 4. Combination of digitally high and low-pass filtered signals is used to locate the individual axles (Figure 4, right). Different signal thresholds are applied to first point out the axle group areas, containing either single or multiple axles, and then the individual axles from the axle groups. If light vehicles are seen in the strain signals, as in Figure 2, bottom-right, another threshold is used to identify those. An axle position is defined at the maximum value of the peak and this value is written into channels used for axle detectors. From there on, the SiWIM system applies the same procedures as for an axle detector installation.

Results show that this approach vastly increases number of correctly identified axles on various types of bridges and its further improvements are currently being implemented.

It should be noted that generally the NOR algorithm will catch more vehicles than the conventional axle detector system. The reason is that a vehicle is triggered *always* when a threshold in the signal is attained, which is at all times when something heavy enough is on the bridge. On the other hand, the axle detectors may from different reasons produce signals which can be misinterpreted. This can results in too many or too few axles and consequently, in wrong axle loads.

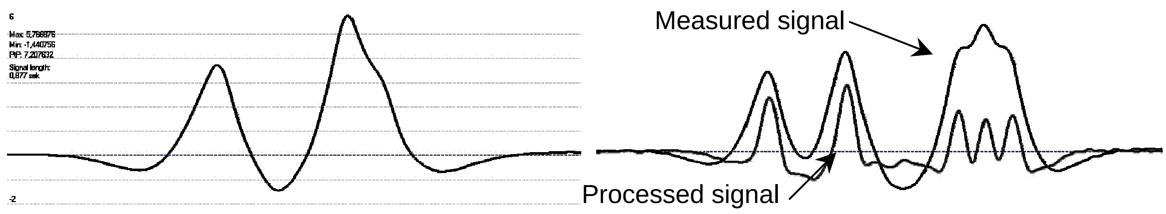

Figure 4 – Signals of a 3-axle (left) and a 5-axle vehicle - original and processed (right)

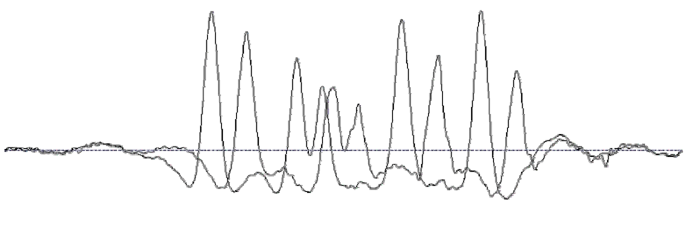

Figure 3 – Signals at 2 different longitudinal positions used for axle detection

4.2 Results – identification of axles and vehicles

Efficiency of the new NOR axle detection was tested on 2 extreme cases from Figure 2, on the thick slab with smeared peaks and on the beam-deck bridge with distinct peaks. In the first case, a one hour video of all traffic was recorded and was visually compared to the NOR results calculated by the SiWIM system. Detailed analysis showed (Table 1) that from the 202 heavy vehicles recorded on the tape, 182 or 90,0% had the correct number of axles, but the axle distances varied for up to 15 cm, which for 19 (additional 9,5%) of these 182 vehicles meant that they were not correctly classified. Three heavy vehicles from the tape were not found in the results, and three non-existent vehicles were identified as a result of noise in the signal. Most of these problems, primarily caused by light, unloaded vehicles, will mitigate with the next generation of the SiWIM software, currently being developed. It will remove such errors automatically by correlating the measured and the modelled bridge responses. SiWIM already calculates a correlation factor between the measured and the modelled signals which indicates incorrect number of axles, but automatic corrections of the result is not being used yet.

Results from the beam-deck bridge with instrumented slab between the beams (Figure 2, bottom-right) were considerably better. It should be noted that the initial SiWIM installation on this bridge used axle detectors. The NOR sensors were added later and, consequently, NOR results were obtained entirely by post-processing of the stored strain data, as triggered *by the axle detectors*. One of the ten days of measurements was analysed. In that day the axle detector system weighed 260 vehicles with the gross weight above 5 tons. The NOR algorithm did 261. One vehicle was not detected, because it was driving on the other lane where there were no NOR sensors. On the other hand, 2 additional vehicles not identified with the AD system were captured (there can be more closely spaced vehicles stored in one file). This number would probably be even higher during real-time measurements because if the AD system miss performed, no files were saved and thus NOR was not possible. Furthermore, from all axles of the 261 vehicles the NOR algorithm missed only one single axle. It belonged to a very light trailer.

Table 1 – Incorrectly detected vehicles and axles on a thick slab bridge

Miss detected	missing	too many
Vehicle	3 (1,5%)	3 (1,5%)
1 axle	7 (3,5%)	2 (1,0%)
2 axles	4 (2,0%)	1 (0,5%)
3 axles or more	0	0
	14 (6,9%)	6 (3,0%)

4.3 Results – Weighing Accuracy

In the second stage of evaluation, accuracy of NOR results on two bridges was evaluated. To compare static with WIM results we have used random traffic on the thick slab motorway bridge and two pre-weighed vehicles on the beam-deck one.
In the first case 43 random vehicles were weighed statically on a portable axle weighing scale installed on a rest area around 2 km after the WIM site. As in the past (WAVE 2002) the static weighing itself proved to be a difficult task despite taking photographs of all vehicles on the WIM site and on the static scale. At high expected weighing accuracies the major problem observed was the behaviour of drivers. With lifting axles on many of modern heavy vehicles it is very difficult to prevent that their position (raised or lowered) has not changed from WIM to static weighing. Furthermore, a few drivers changed the air pressure in the suspension during the

static weighing procedure, causing changes in axle loads in excess of 20%. It is therefore realistic to assume, that the true accuracy was better than it could have been proved. A static weigh bridge in combination with the static or low-speed axle weighers would solve this problem, but no weigh bridge was available near the site.

Nevertheless, accuracy of the results was high, which was expected due to the excellent pavement. Table 2 gives several accuracy calculations based on COST 323 methodology:

1. First, all 43 vehicles were taken to calculate the calibration factor (initial calibration in full reproducibility conditions). Two different calibration factors were used, for short rigid and for longer articulated vehicles.
2. The same procedure was repeated only for the 33 long, non-rigid vehicles.
3. The first 10 long vehicles were used to calculate the calibration factor to perform initial calibration in limited reproducibility conditions.
4. The calibration factor from 3 was used for the other 24 long vehicles.
5. As in 4, but with additional 10 short vehicles, including some very light ones.
6. As in 4, but only for vehicles heavier than 12 tonnes.

Detailed results are presented in Table 2.

There were not enough heavy rigid 2 or 3 axle vehicles weighed to apply 2 different calibrations factors for rigid and for articulated vehicles. It is can be assumed that this would further improve accuracy of the results.

Figure 5 – Calibration with Random Traffic on a Portable Axle Weigher

The beam-deck bridge was calibrated with a 3-axle rigid truck and a 5-axle semi-trailer. The strain transducers for axle detection were mounted on the slab, while strain transducers for weighing were attached to the beams at midspan. Only lane 1 was instrumented with additional NOR sensors. Due to its span length, the gross vehicle weights were considerably more accurate than the axle loads, even in the very uneven lane 1. Influence of the pavement quality is however very obvious (cases 1 and 2 for lanes 1 and 2 in Table 3 and Figure 6).

Table 2 – Accuracy results with axle detectors and NOR

All vehicles for calibration						Initial calibraiton: Yes		
	Number	Mean value	Std.dev.	δ_{crit}	δ_{class}	π	π_{crit}	Class
GVW	43	0,00	3,89	9,9	10	90,9	91,2	B(10)
Group	37	0,75	3,60	6,6	7	90,4	92,8	B+(7)
Single	82	-0,67	5,40	9,1	10	92,5	95,0	B(10)
All long vehicles for calibration						Initial calibraiton: Yes		
	Number	Mean value	Std.dev.	δ_{crit}	δ_{class}	π	π_{crit}	Class
GVW	33	0,00	2,69	6,9	7	90,0	90,7	B+(7)
Group	35	0,85	3,66	6,7	7	90,2	91,9	B+(7)
Single	64	-0,89	4,35	7,2	10	92,0	98,3	B(10)
First 10 long vehicles for calibration factor						Initial calibraiton: Yes		
	Number	Mean value	Std.dev.	δ_{crit}	δ_{class}	π	π_{crit}	Class
GVW	10	0,00	2,28	6,0	7	80,1	88,3	B+(7)
Group	10	0,98	3,48	6,5	7	80,1	84,1	B+(7)
Single	20	-0,75	3,53	5,9	7	87,5	93,7	B+(7)
All other long vehicles						Initial calibraiton: No		
	Number	Mean value	Std.dev.	δ_{crit}	δ_{class}	π	π_{crit}	Class
GVW	24	0,72	3,11	6,5	7	88,5	91,3	B+(7)
Group	26	1,67	4,21	6,4	7	89,0	92,3	B+(7)
Single	46	-0,32	4,64	6,0	7	91,1	95,4	B+(7)
All other vehicles						Initial calibraiton: No		
	Number	Mean value	Std.dev.	δ_{crit}	δ_{class}	π	π_{crit}	Class
GVW	34	0,67	4,37	9,0	10	90,1	93,6	B(10)
Group	28	1,49	4,36	6,5	7	89,3	91,9	B+(7)
Single	64	-0,26	5,98	7,9	10	92,0	97,3	B(10)
All other long vehicles with GVW>12 tonnes						Initial calibraiton: No		
	Number	Mean value	Std.dev.	δ_{crit}	δ_{class}	π	π_{crit}	Class
GVW	29	1,41	3,07	6,8	7	89,5	90,7	B+(7)
Group	27	1,97	4,06	6,3	7	89,1	92,8	B+(7)
Single	54	0,80	5,11	6,7	7	91,6	92,9	B+(7)

In the very smooth lane 2 accuracy class A(5) was achieved for the gross weight and group of axles criteria, which was excellent, having in mind the profound dynamic behaviour of the bridge. Figure 7 shows the difference in dynamic behaviour of a 5 and a 3-axle vehicle following each other. The individual axle load criteria gave a still very good class C(15). Results of the other lane with a heavy bump around the extension joint were worse, from a still very good class B+(7) for the gross weights to the extremely bad E(145) for individual axles. The reason for it was serious redistribution of the axle loads of vehicles that 'jumped' on the bridge (Figure 6). Yet, when an automatic procedure was applied to divide the very accurate gross weights into individual axle loads according to the height of individual peaks from the NOR strain transducers (Figure 2, bottom-right), accuracy results improved significantly (case 3).

In lane 1 the same accuracy calculation procedure was then repeated for the NOR installation (case 4). Compared to case 1, the results were slightly worse. No detailed analysis has been done yet but one of the obvious reasons was the less accurate acquisition of axle spacings compared to the axle detectors (no sharp peaks as with axle detectors). However, when the same peak redistribution procedure as in case C was applied, improvements were significant (case 5). When in addition all axles from the groups were taken as equally loaded, a very respectable accuracy class for such a bad pavement, D+(20), was obtained (case 6). Unfortunately, NOR instrumentation of lane 2 was not done, but it can be realistically expected that, based on case 2, more accurate results would have been achieved. All results are given in Figure 8.

Table 3 – Accuracy results with axle detectors and NOR

Case	Accuracy of	GVW	Group of axles	Single axles
A	Axle detectors lane 1, conventional SiWIM	B+(7)	E(30)	E(145)
B	Axle detectors lane 2, conventional SiWIM	A(5)	A(5)	C(15)
C	Axle detectors lane 1, peak redistribution	B+(7)	D+(20)	E(55)
D	NOR lane 1, conventional SiWIM	C(15)	E(35)	E(175)
E	NOR lane 1, peak redistribution	C(15)	D(25)	E(60)
F	NOR lane 1, axle group redistribution	C(15)	C(15)	D+(20)

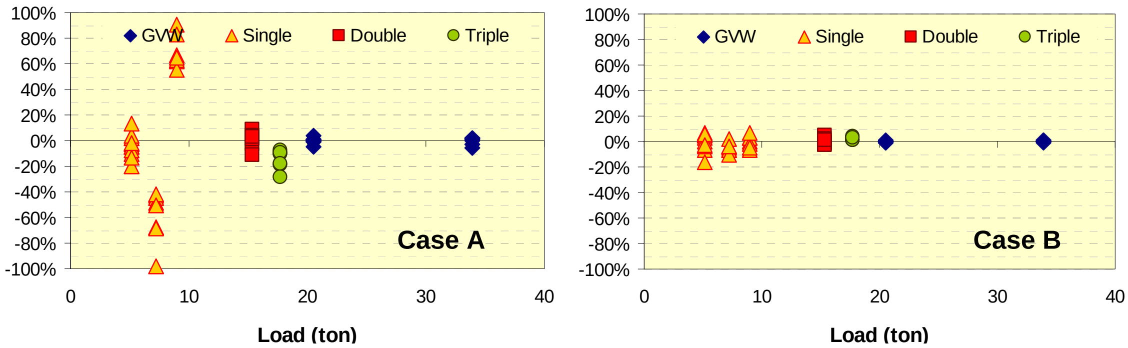

Figure 6 – Results of Calibration: Lane with the Bump (Left), Smooth Lane (Right)

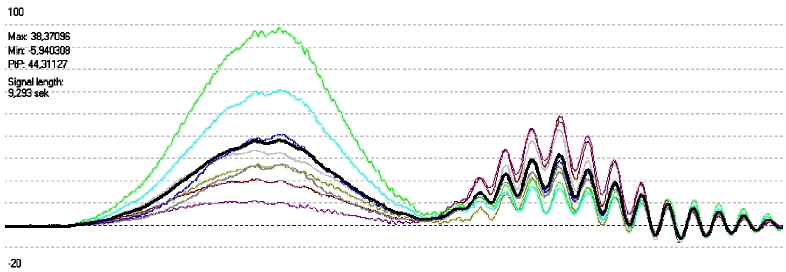

Figure 7 – Dynamics of Strain Signals from the Calibration Vehicles: 5-axle Semi-trailer and 3-axle Rigid Truck, Following each Other

5. Conclusions

Instead of different types of axle detectors the bridge WIM system can often use strain sensors located underneath the bridge to detect axles. This method is known as NOR (Nothing On the Road) or FAD (Free-of-Axle Detector) bridge WIM system.

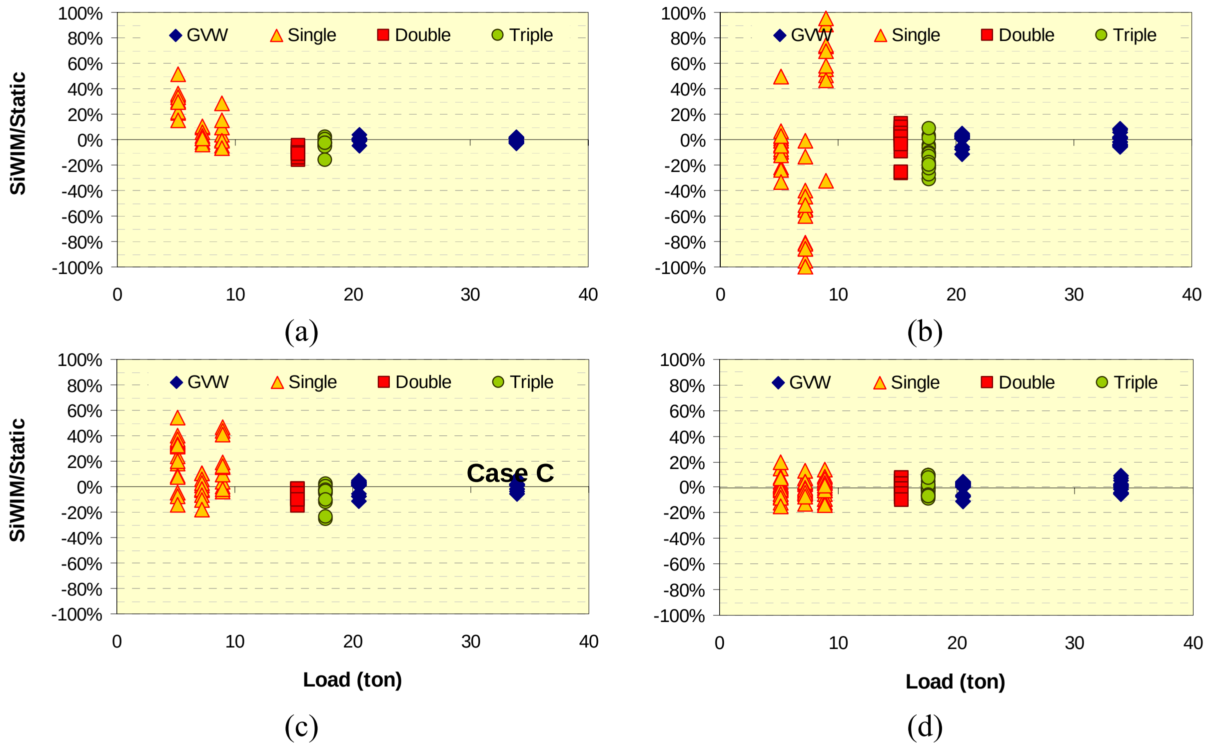

Figure 24 – Improvement of the Calibration Results According to the Table 2

With the latest developments the number of different types of bridges suitable for NOR increased and includes slab bridges, beam-deck bridges and orthotropic deck bridges. Variety of bridge types produces a variety of shapes of strain signals used for detecting the axles. They can have a high dynamic component in the measured signals or can produce heavily smeared signals which make individual, especially light axles difficult to locate.

A new algorithm which deals with most types of strain signals was developed. It first cross correlates two signals from different longitudinal locations to obtain the vehicle velocity. Then, a combination of low- and high-pass filtering is applied to extract the individual axle spacings.

Comparison to the videotaped traffic showed that the identification rate was good even on the bridge with the highly smeared signals. On such bridges the original NOR method, proposed in WAVE, would successfully identify only a few multiple axles. On the other hand, the experiment on a beam-deck bridge showed that by combining high accuracy of GVW results with the NOR signals, accuracy of results was greatly improved. This is encouraging, especially as on this bridge in some cases the dynamic amplifications reached 100% and as almost 40% of all cases used in calculation were the multiple-presence events, with at least 2 vehicles on the span.

Consequently, in Slovenia around 20 bridges (almost 50% of all bridges instrumented for WIM) in 2004 have been instrumented without axle detectors and this number is growing each year.

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BRIDGE WIM BY REACTION FORCE METHOD

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Professor, Nagoya University. 1971 MS Nagoya University, 1975 Ph.D. University of Maryland. Research interest in fatigue problems of welded structures and fracture mechanics, and durability evaluation

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Abstract

This paper proposes a method of axle-detector-free Bridge Weigh-in-Motion called the Reaction Force Method. When a truck runs over the bridge, sharp edges occur in the reaction force response wave. The amount of the edges corresponds linearly to independent axle loads. Instrumentation is carried out at both sides of a bridge. Velocity of trucks can be estimated through comparison with edge patterns in the two reaction forces. Simple supported steel plate girder bridges with no skew angle are suitable for this method. Strain gauges are attached on end vertical stiffeners just above bridge supports. This paper describes the method’s principle, its accuracy, and results of 168 hours’ truck load monitoring.

Keywords: BWIM, Bridge Weigh-in-Motion, Axle Detector Free, Reaction Force.

Résumé

Cet article décrit une méthode de "Pesage en marche par ponts intrumentés" sans détecteurs d'essieu dite "Méthode par force de réaction". Quand un poids lourd passe sur un pont, l'onde de réponse de la force de réaction montre des arêtes saillantes. L'amplitude de ces arêtes correspond linéairement à la charge des essieux individuels. Les instruments de mesure sont placés des deux côtés du pont. La vitesse du poids lourd peut être calculée par comparaison des formes d'arêtes des deux forces de réaction mesurées. Les ponts à poutres en tôles d'acier à simple support sans contact oblique sont parfaitement adaptés à ce type de méthode. Des jauges de contrainte sont fixées sur les raidisseurs verticaux d'extrémité, immédiatement au-dessus des supports du pont. Cet article décrit les principes de la méthode, sa précision et les résultats obtenus après un contrôle de la charge de poids lourds pendant 168 heures.

Mots-clés : BWIM, Pesage en Marche par Ponts Intrumentés, Sans Détecteur D'essieu, Force de Réaction.

反力法於橋樑動態地磅載重之應用

摘要：

本文章提出一種不需車軸偵測器之橋樑動態載重量測法 (Bridge Weigh-in-Motion, BWIM)，稱之為反力法 (Reaction Force Method) 。當卡車通過橋樑時反力波會產生尖峰值，而該值與個別之軸重呈現線性關係。本研究於橋樑的兩端裝設儀器以量測相關數據，因此車速可由橋樑兩端反力波尖峰值發生之時間點推知。本法適用於與車行方向無斜交之簡支承鋼板梁橋，而應變計則安裝於橋樑支承之垂直加固物上。本文主要描述該方法之理論、正確性以及 168 小時重車載重監測之分析結果。

關鍵字：橋樑動態量測法、不需車軸偵測器、反力

1. Introduction

About 14,000 highway bridges in Japan are longer than 15 m. Most were constructed during the 1960s to the 1980s. Fatigue design was not applied to those bridges at that time because there was no specification for fatigue. Recently, fatigue problems in steel highway bridges have been highlighted in these bridges. Several studies have reported that these fatigue failures are mainly attributable to fabrication or design processes: low quality of welding, plate misalignment, lack of fatigue strength, and so on. New design specifications for highway bridges were published in March 2002. Thereby, the total design life of steel bridges was specified clearly as 100 years and fatigue design finally became a requirement. Nevertheless, heavy truck loads and their frequency are a cause of these failures. Truck freight overtook railway freight in the 1960s in Japan.

Accordingly, the number of trucks increased. Truck manufacturers have improved truck durability. Consequently, truck load capacity has increased. Furthermore, the Ministry of Land, Infrastructure and Transportation (MLIT) changed the limit of gross vehicle weight on highways in 1994. The maximum gross vehicle weight of a typical three-axle truck was raised from 200 kN to 250 kN. Notwithstanding, penalties for overweight transport have not changed, and there are insufficient facilities or management system to control overloaded trucks. Several surveys of traffic loads have reported that many overloaded trucks burden toll-free national routes. Overloaded trucks tend to use toll-free national routes because the Japan Highway Public Corporation (JH) placed axle load scales at their tollgates to give warnings to truck drivers.

The Weigh-in-Motion (WIM) method was first introduced to Japan in 1968 by JH. They carried out a practical study of a dynamic weigh scale on Meishin Expressway. After the test, JH installed seventeen WIM stations on the Tomei Expressway in the same year. Several WIM stations are now in service on expressways of JH. MLIT now have eighteen WIM stations on national highways. Some have automatic vehicle identification; one has multiple sensors. Recently, a national highway WIM network is being planned by the MLIT. Thirty WIM stations are planned to have license plate number identification, multiple sensors, and warning systems. They will be installed on major national routes. A traffic load survey is being planned with bridge WIM to determine efficient locations for these WIM stations. The MLIT tested BWIM using several type of bridges based on a method proposed by Fred Moses (Moses, 1979).

Bridge WIM (BWIM) without an axle detector is suitable for temporary use, such as surveys of truck load statistics or spot checks of overloaded trucks. BWIM systems without axle detectors were developed in Japan after work by F. Moses (Moses, 1979). A BWIM method for steel plate girder bridges was proposed by Miki et al. (Miki, 1987). Matsui et al. used cracks in reinforced concrete decks to identify axle loads (Matsui, 1989). The authors developed a BWIM system using longitudinal ribs of an orthotropic steel deck of a box girder bridge (Ojio, 1997). The authors also developed a BWIM system that uses stringers of plate girder bridges (Ojio, 2002). These BWIM methods detected axle loads from the bending moment of bridge members.

However, when such a BWIM uses long influence lines and wide influence surfaces, its accuracy is affected by multiple existences of trucks on bridge surfaces. On the other hand, short influence lines and narrow influence surfaces are sometimes too sensitive to the transverse locations of trucks.

The main intention of the method proposed in this paper, Reaction Force Method, is to obtain an alternative approach of BWIM that does not depend on bending moment. The calculation procedures are simpler than for other methods. It does not need influence line. Axle detection and axle load calculations are carried out simultaneously. Furthermore, each axle load is calculated independently. Sensors are installed only on bridge supports, which are more easily accessible than other bridge members.

2. Reaction Force Method

2.1 Principle of the Reaction Force Method

The authors propose an alternative BWIM approach: Reaction Force Method. Using no inverse analysis, it estimates axle loads independently from the difference of reaction force.

It is based on a simple concept. The influence line of reaction force in a simple supported girder bridge is shown in Figure 1. It has a sharp edge just at the support. Figure 2 shows the reaction force response to loading by a three-axle truck. The amount of each edge corresponds to the axle load. Therefore, axle loads are obtained independently from edges in the reaction force.

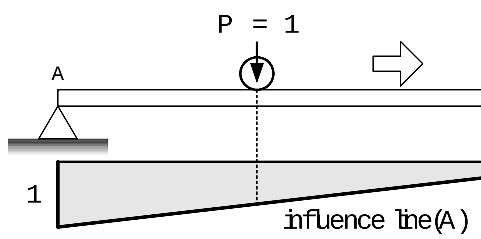


Figure 1 - Influence Line of Reaction Force

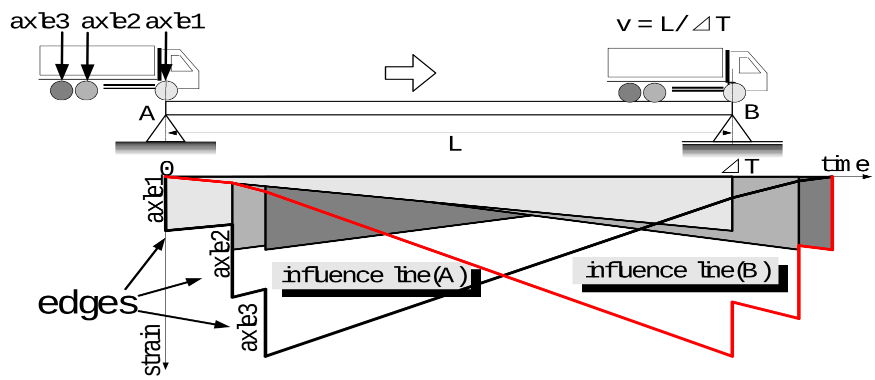


Figure 2 - Reaction Force by a Three-axle Truck

The overall shape of influence line need not match that of the theoretical shape, but the edge must be sharp enough to identify tandem axles. Only squared bridges are recommended for this method. When a truck tire passes the expansion joint of a right-angled bridge, a sharp edge occurs in the reaction force. However, if a skew angle exists, left and right tires arrive the expansion joint 'softly' and separately, and the reaction force changes more gradually. In this case, the influence line does not have any sharp edge on the support. Additionally, in some cases of experimental studies, sharp edges were not observed in steel plate girder bridges because of expansion joint malfunction or bearing deterioration. Therefore, edges in strain waves must be checked in advance.

2.2 Application to Steel Plate Girder Bridges

Measurement of Reaction Force

Yamada carried out a practical study for measuring reaction force (Yamada, 1997). Strain gauges were attached at end vertical stiffeners above supports in a steel plate girder bridge. It was reported that strain at the end vertical stiffener was proportional to the reaction force.

The authors applied this reaction force method to steel plate girder bridges, which are among the most popular mid-span highway bridges in Japan. Strain gauges are attached at the end vertical stiffeners located on both sides of the bridge, as shown in Figure 3. The velocity of trucks is estimated by comparison of edge patterns on both sides of the bridge. Axle spacing is estimated by the interval of axles; the truck class is classified by axle spacing patterns, as shown in Figure 4.

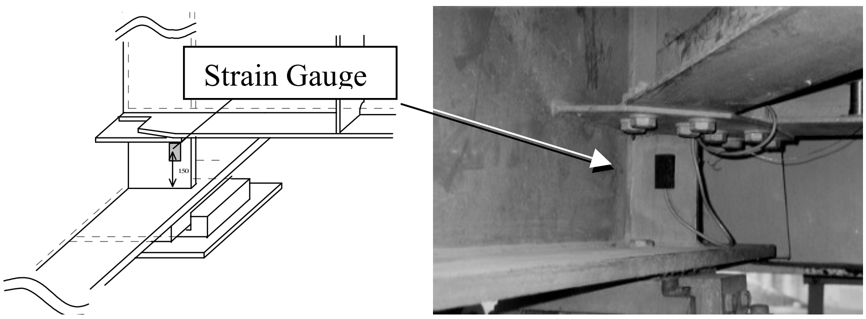


Figure 3 - Strain Gauge Locations at End Vertical Stiffeners

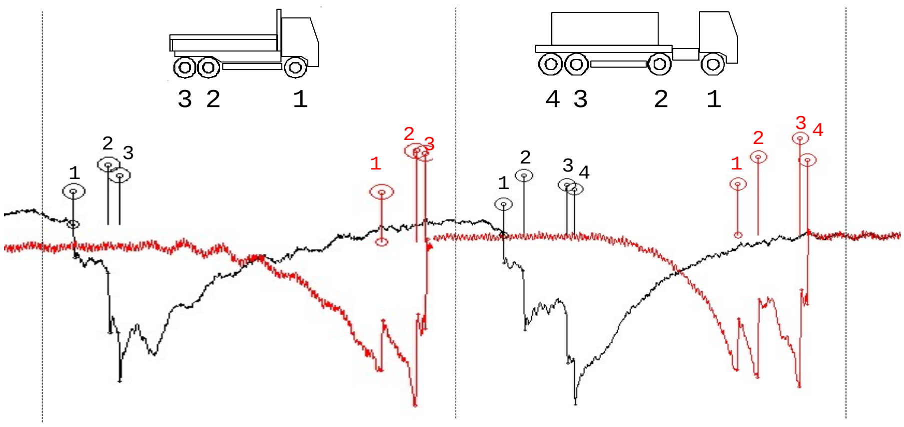


Figure 4 - Velocity Estimation and Truck Type Classification

Sensor Arrangement

Figure 5 shows examples of sensor arrangements for multiple steel plate girder bridges. In the first two cases, axle loads are calculated independently even if two axle loads pass on the bridge end at the same time. In example (a), support A and support D react for truck loads on each lane. However, edges in the response wave are observed only when axle loads are on lane 1: even if an axle load on lane 2 is at the bridge end, it is not distributed to support A. The influence line at support A for lane 2 has no sharp edge. Therefore, axle loads can be detected independently for each lane from supports A and D. This arrangement greatly simplifies the calculation algorithm. On the other hand, the scatter of the transverse location of trucks affects the axle load accuracy because calibration values are measured on the lane center. Supports B and D in example (b) are sensors for lanes 1 and 2. In this case, axle loads on each lane are detected independently. Even if a truck runs with variation in its transverse location, the reaction force on the supports indicates a constant value because of the balance of variations by left and right wheel.

Measuring at all bridge supports in example (c) is a fundamental approach of BWIM. The occupied lane can be detected by the distribution of reaction forces at all bridge supports. The axle load on lane 1 is calculated by supports A and B, that of lane 2 is calculated by supports B and C. However, axle loads pass on the bridge end at the same time as in this figure. Axle loads on each lane can not be calculated independently: a simultaneous equation is required to obtain each axle load.

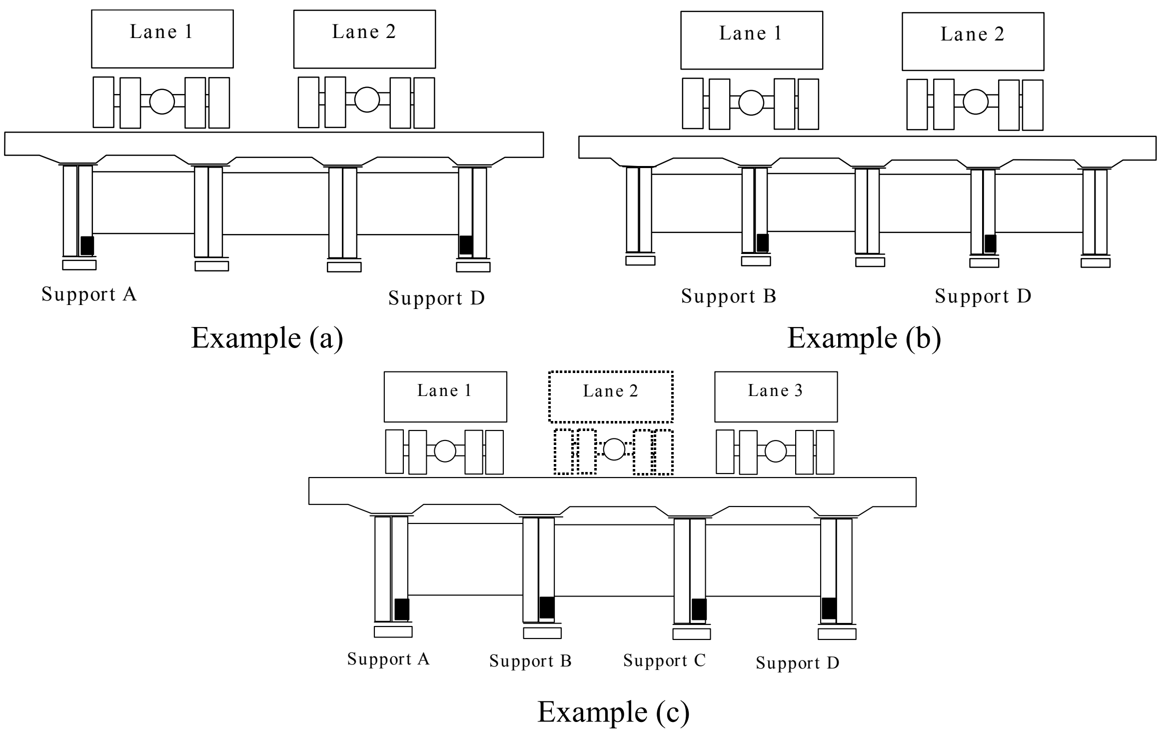


Figure 5 - Examples of Sensor Arrangements in Steel Plate Girder Bridges

2.3 Test on Highway Bridges

Test Bridge

Experimental studies using the reaction force method were carried out at two highway bridges near Nagoya. Yokkaichi viaduct in National Route 23 (NR23), shown in Figure 6, is located southwest of Nagoya. Huge petrochemical complexes and numerous heavy industry installations are located in this area. According to a 1999 traffic census, NR23 carries 63,390 vehicles per day; 45% of them are trucks. The Kojima viaduct on the Higashi Meihan Expressway (HM Expressway) is located west of Nagoya. It carries 67,678 vehicles per day; 29% of them are trucks.

(a) Yokkaichi Viaduct (b) Kojima Viaduct

Figure 6 - Bridge Sites for Experimental Studies

Sensor arrangements were decided on simplifying the BWIM algorithm, as shown in Figures 7 and 8. These sensors can detect axle loads independently on each lane.

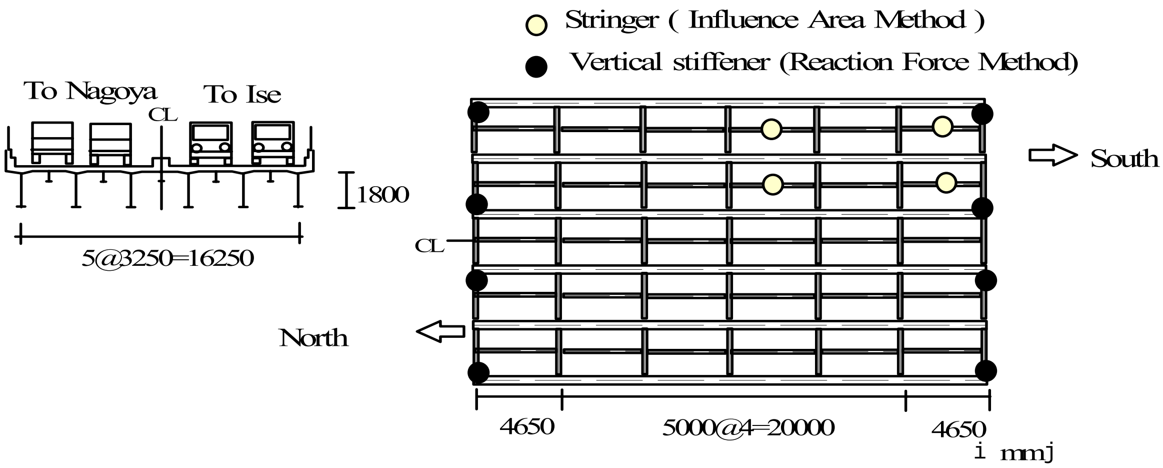


Figure 7 - Sensor Arrangements for the Yokkaichi Viaduct

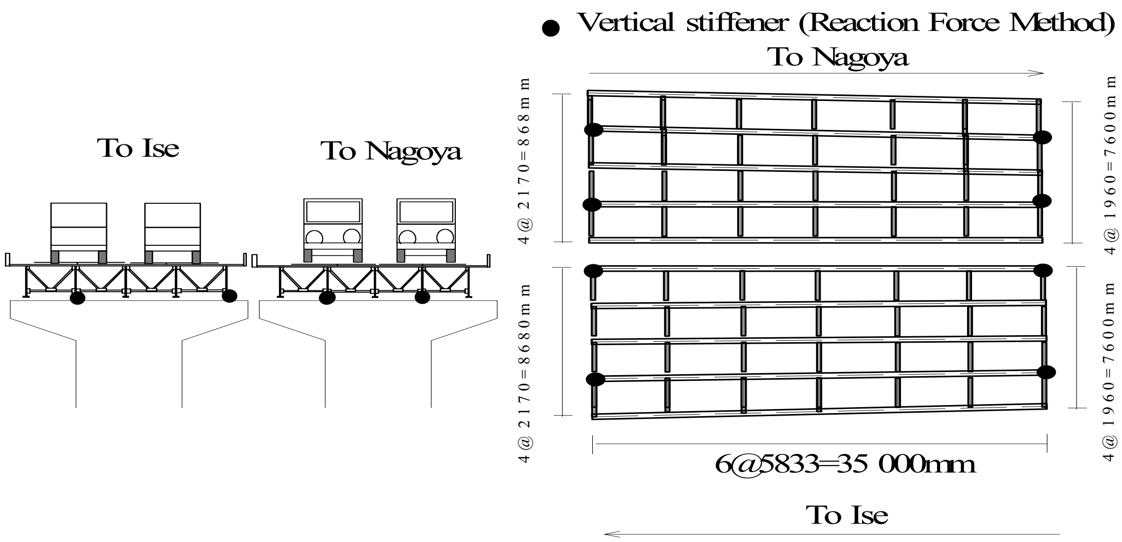


Figure 8 - Sensor Arrangements for the Kojima Viaduct

Calibration and accuracy

Strain data were measured at 0.005-s sampling times (frequency: 200 Hz). Strain sensitivity of the digital dynamic strain recorder was set to 1-digit for 0.1 micro strains (0.1 × 10E-6 strains). No filter was used for the strain signal because filtering under 100 Hz makes the edge of the strain signal smooth. To reduce noise, a noise isolation transformer was used for the power supply and the ground point of the shield cable was tested carefully. The algorithm for detecting edges in strain waves was verified for test trucks and other trucks measured in calibration tests. Figure 9 shows an example of strain waves measured at the Kojima viaduct. In this case, the sensor arrangement was as example (b) in Figure 5. A three-axle truck ran over the slow lane. Three edges were observed in support B. Edges were observed at two or three sampling times: 0.010 or 0.015 s.

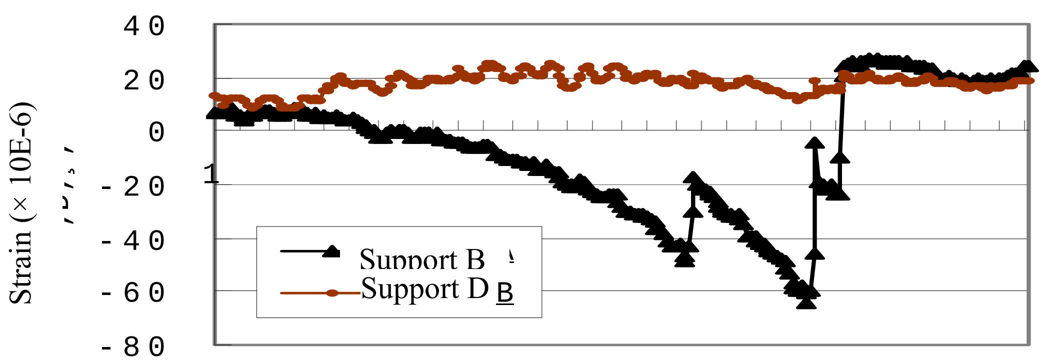
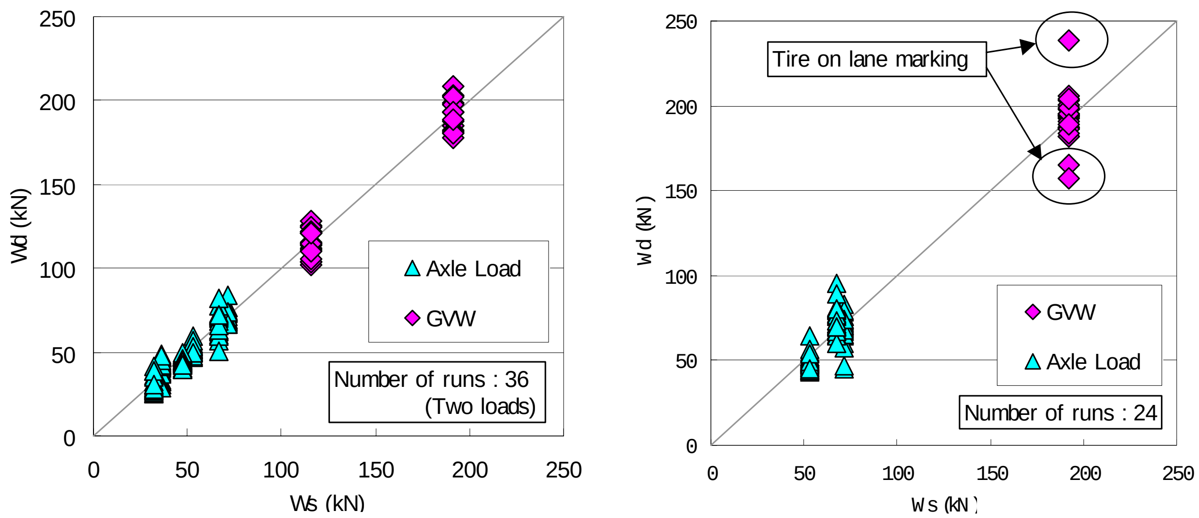


Figure 9 - Examples of Strain Waves at Vertical Stiffeners

Figure 10 shows results for test trucks at initial verifications. Axle loads were calculated by averaging the results obtained at both ends of the bridge. According to accuracy by one or two test trucks (a 3-axle rigid truck) with 36 or 24 test runs, accuracy classes for GVW in the European WIM specification were D+(20) in the Yokkaichi viaduct, D(25) in the Kojima viaduct. When the test truck runs on the left of right bound the lanes in three cases (bound to Ise) at Kojima Viaduct, errors were observed: they were caused by the transverse location of the trucks. Accuracy might be improved if sensor arrangements are modified as example (c) in Figure 5.

Axle spacing for test trucks was estimated with accuracy of 5% when the truck speed was 40 km/h – 80 km/h. That is sufficient accuracy to identify axle spacing of tandem or tridem axles of trucks. Therefore, the truck type was classified by axle spacing patterns in the following experiments.



(a) Yokkaichi Viaduct (b) Kojima Viaduct

Figure 10 - Axle Load and GVW Estimation Results for Test Trucks

2.4 Study using a truss bridge

Some vertical members of deck truss bridges are sensitive to vehicle loads when they support a panel of the bridge deck. The influence line of the end vertical member has an edge at the bridge end. An experimental study for application of the reaction force method to truss bridges was carried out using a Warren truss bridge. Figure 11 shows the elevation of the Arakawa Bridge. One strain gauge was attached at an end vertical member. Example of strain wave for a test truck is shown in Figure 12.

Three edges were observed at the arrivals of axle loads. There were insufficient data to evaluate accuracy of this approach. However, the reaction force method might be applied to this type of deck truss bridge.

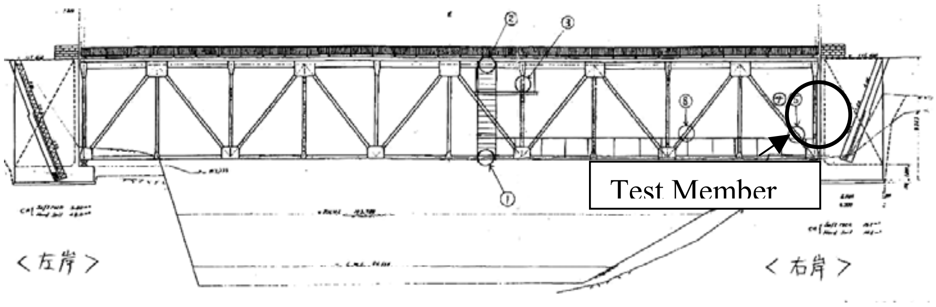


Figure 11 - Elevation of the Arakawa Bridge

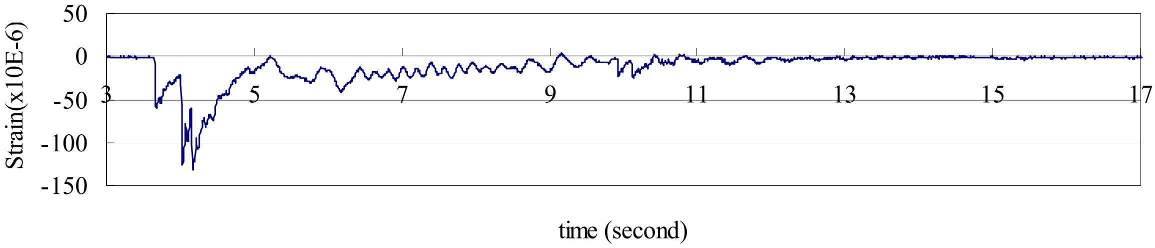


Figure 12 - Response Wave for Test Truck (Three-axle Damp Truck with GVW of 196 kN)

3. Traffic Load Monitoring by Reaction Force Method

3.1 BWIM program

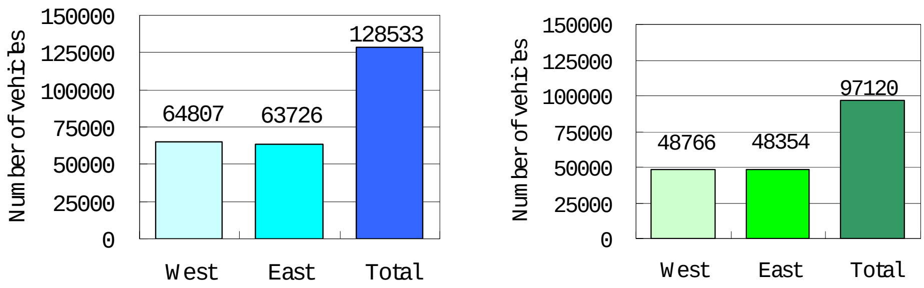
The BWIM program was developed for this Reaction Force Method. This program was designed for the two test sites as mentioned above. Each traffic lane was analyzed independently. The outline of the calculation procedure was as follows:

1) Detection of axle loads by edge detection from the strain wave
2) Making a group of axles (or vehicles) at both bridge ends
3) Pattern matching of the group of axles (or vehicles) between both bridge ends
4) Velocity calculation
5) Axle-spacing calculation
6) Vehicle identification from axle spacing
7) Truck-type classification

Axle detection and axle load calculation were carried out only in process 1).

3.2 Results of long term monitoring

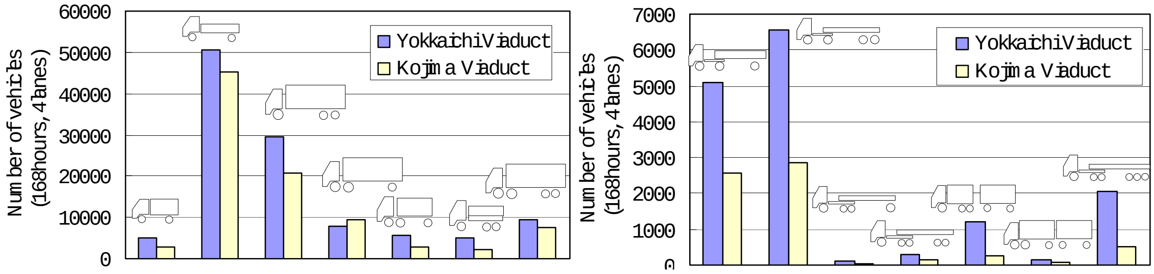
Long-term tests in service were carried out at Yokkaichi viaduct and Kojima Viaduct for 168 hours (h). Strain waves were recorded in a sampling time of 0.005 s. The lower limit of detectable axle loads was approximately 20 kN. The total number of vehicles that were identified correctly from BWIM is shown in Figure 13: 128,000 trucks were identified at the Yokkaichi viaduct, and 97,000 at the Kojima viaduct. The rate of truck traffic volume identified by BWIM, for that in the traffic census, indicated 76% at Yokkaichi viaduct, 85% at Kojima viaduct. However, the volume in the traffic census includes light trucks, which have gross vehicle weight under 40 kN when not loaded.



Yokkaichi viaduct Kojima viaduct

Figure 13 - Total Number of Identified Vehicles for 168 h

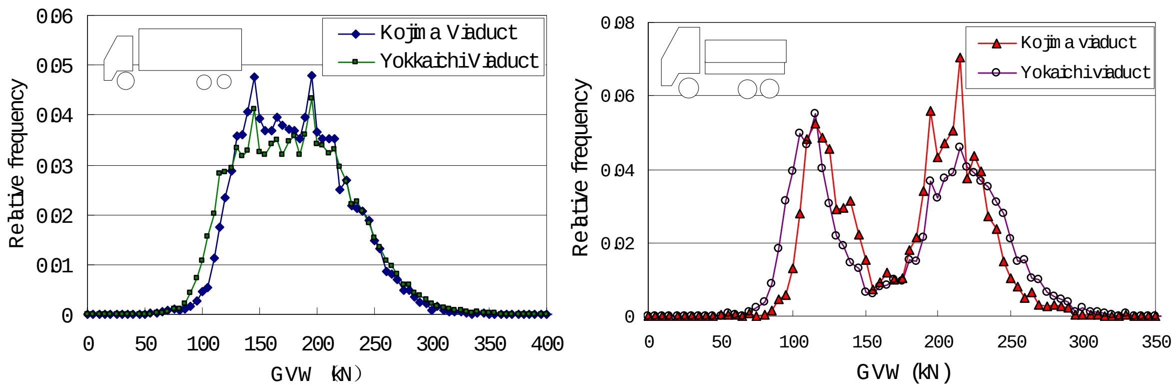
Figure 14 shows the number of trucks processed at the two test sites. Freight companies in Japan mainly use rigid trucks.



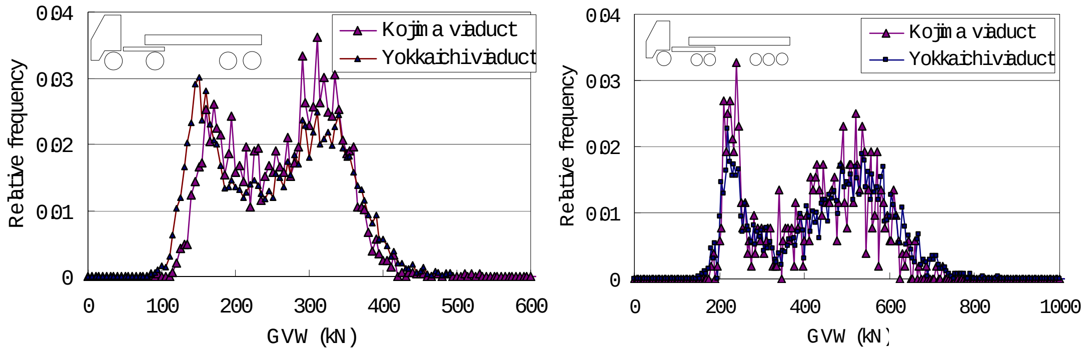
Rigid trucks Semi/Full trailers

Figure 14 - Number of Trucks Obtained by Long Term Monitoring Test for 168 h

Examples of relative frequency diagrams of gross vehicle weights for several truck types are shown in Figure 15.



3-axle, rear tandem, long 3-axle rear tandem, short



4-axle, semi-trailer, 2+2 6-axle, semi-trailer, 3+3

Figure 15 - Examples of Relative Frequency Diagrams of GVW for Several Truck Types

4. Summary of Findings

A Bridge Weigh-in-Motion method without an axle detector was proposed herein. Axle loads are estimated from edges in response wave of reaction force. Strain, which corresponds to reaction force, is measured at the end vertical stiffeners of steel plate girder bridges. Experimental studies were carried out at two steel plate girder bridges. Accuracies of BWIM were checked with test trucks. Truck load statistics were obtained at two bridges through long term monitoring for 168 h. Following is a summary of results.

1) Strain at end vertical stiffeners of steel plate girder bridges indicates the component of reaction force.
2) Edges in the strain wave at end vertical stiffeners corresponded to truck axle-loads.
3) Accuracy of BWIM by this Reaction Force Method at two highway bridges was D+(20) and D(25) for GVW in the accuracy class of European Weigh-in-Motion Specifications.
4) Variations of transverse location of test trucks caused errors of axle loads in some sensor arrangements, but they are canceled in other sensor arrangements.
5) Accuracies of axle spacing were sufficiently good to identify truck types.
6) This Reaction Force Method might be applied to vertical members of some deck truss bridges.
7) Total numbers of trucks processed at two test sites were 76% or 85% for the data in the traffic census. However, the census data includes light trucks.

Acknowledgements

This research was carried out with the help of a Grant-in-Aid from the Ministry of Education, Science, Culture and Sports, Japan (No. 15760347, Tatsuya Ojio). This paper was written with the help of a grant from the Nitto foundation. The authors are grateful to the Ministry of Land, Infrastructure and Transportation, the Japan Highway Public Corporation for allowing our measurements. The authors are also grateful to Dai-Ichi Giken Consultant, Aisoku Engineering, and the Tokyo Sokki Kenkyujo for supporting our measurements.

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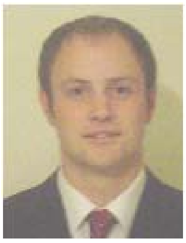
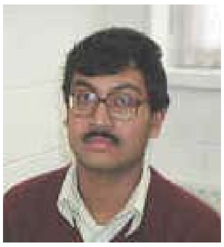
BRIDGE WIM SYSTEMS WITH NOTHING ON THE ROAD (NOR)



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Abstract

This paper develops the concept of a Nothing On Road (NOR) Bridge Weigh-In-Motion (B-WIM) system, where only the strain gauges or transducers underneath the bridge are used to identify vehicle occurrences, velocities, numbers of axles and axle spacings. In traditional B-WIM systems, axle detectors on the pavement surface are used to provide this information. As they are directly exposed to traffic loads, they are prone to deterioration and are much less durable than the rest of the system. Furthermore, axle-detector installation and maintenance represents a significant safety issue. This paper describes the use of a wavelet transform of the strain signal to give a clear indication of the location of closely spaced axles.

Keywords: WIM, Weigh-In-Motion, Bridge, NOR, Axle, Detectors, Wavelet, Durability.

Résumé

Cet article développe le concept de pesage en marche par pont instrumenté (B-WIM) sans « rien sur la route » (NOR). Ceci signifie que seuls les jauges ou capteurs de déplacement placés sous le pont sont utilisés pour identifier les passages de véhicules, leurs vitesses, nombre d’essieux et distances entre essieux. Dans le pesage par ponts instrumentés traditionnel des détecteurs d’essieux posés sur/dans la chaussée sont utilisés pour recueillir ces informations. Mais comme ces capteurs sont exposés aux charges de trafic, ils subissent des détériorations et sont beaucoup moins durables que le reste du système. En outre leur installation et maintenance pose de sérieux problèmes de sécurité. On décrit l’utilisation de transformée en ondelettes des signaux de déformation pour donner une indication précise sur la localisation des essieux rapprochés.

Mots-clés: Pesage en Marche, Pont, NOR, Essieu, Détecteur, Ondelette, Durabilité.

NOTHING-ON-THE-ROAD 之橋梁動態地磅系統

摘要：

本文針對 Nothing-On-the-Road 之橋梁動態地磅（Bridge Weigh-In-Motion, B-WIM）進行探討，該系統僅利用裝設於橋面版下之應變計或感測器量測車輛到來、速度、軸數以及軸距之辨識。傳統之橋梁動態地磅系統利用橋面上之輪軸偵測器獲得上述資訊。但因上述偵測器長期遭車輛碾壓，因此容易損壞且耐久性較整體系統之其餘部分差。再者，輪軸偵測器之安裝以及維護將造成嚴重之安全問題。本研究利用小波轉換應變訊號以清楚地辨識出兩鄰近輪軸之位置。

關鍵字：動態地磅、橋梁、NOR、輪軸、偵測器、小波、耐久性

1. Introduction

In conventional Bridge Weigh-In-Motion (B-WIM) systems, two axle detectors in each lane are used to provide the times of occurrence of each axle of the vehicle and thus the axle spacing, velocity and class. The installation process can require lane closures and associated traffic control measures. By using Nothing On Road (NOR) B-WIM, the durability of the WIM system is greatly increased. Furthermore, the system is not visible to the driver, there is no disruption to traffic flow during installation and cost is reduced.

O'Brien et al (1999), and O'Brien et al (2005) demonstrated the effectiveness of NOR B-WIM using orthotropic bridge decks. Orthotropic bridges are made from stiffened steel and are generally of a low stiffness giving pronounced strain responses to the passing of each axle. He was able to develop an optimisation algorithm to identify the axle positions from the slope of the strain response and demonstrated Class D+(20) accuracy (COST323, 2002) of the NOR algorithm for an experimentally tested orthotropic bridge.

The optimisation algorithm used by O'Brien for orthotropic bridges was based on the minimisation of the sum of the squares of the differences between the strain responses in two successive spans. This is facilitated by near-identical strain responses in the two spans, which does not apply for two locations in a single span bridge. Furthermore, strain signals do not show the effect of individual axles as clearly in deeper concrete bridges where there is a greater degree of load sharing. This paper describes a process of using a wavelet transform to transform the strain signal for all bridge types into a function in which individual axles can be clearly seen.

Theoretical and experimental validations for short slab concrete bridges are carried out using the new approach. Recommendations for the positioning of the strain gauges under the bridge deck are given to minimise bridge-truck dynamic interaction and to maximise the effectiveness of the wavelet transform. Theoretical investigations are undertaken into the possibility of using the new approach for longer span bridges.

2. Review of Wavelet Theory

2.1 Wavelet Analysis

In recent years wavelet theory has emerged as a powerful tool in signal analysis. Wavelets have been applied to the analysis of time-varying signals and special techniques such as discrete and fast wavelet transforms have been developed (Daubechies, 1992). Non-stationary signals from complex dynamical systems have been analysed using wavelets, for linear systems in (Basu and Gupta, 1997, Basu and Gupta, 1998) and for non-linear systems in (Basu and Gupta, 1999a, Basu and Gupta, 1999b). Researchers have also used wavelet techniques for system characterisation, identification and system analysis. It has been used for other purposes such as peak detection, event characterisation, transient analysis and pattern recognition problems. Wavelet analysis is applied to the weigh-in-motion problem in this paper from a pattern recognition point of view.

2.2 Wavelet Representation

The Discrete Wavelet Transform (DWT) is used in this paper, based on a multi-resolution analysis (MRA) framework. A biorthogonal wavelet basis is used. In MRA, there are two scaling functions and two wavelets associated with them. The wavelet used for decomposition is represented by $\psi(x)$. Let $f(x)$ be a square integral function. It can be represented by

$$f(x) = \sum_{k=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} W(k,n).\psi(2^{-k}x - n) \quad (1)$$

where $\psi(2^{-k}x - n)$ is the time basis function and $W(k,n)$ are the wavelet coefficients. In Eq. (1), the function $\psi(2^{-k}x - n)$, often denoted by $\psi_{k,n}(x)$, is obtained by translating the function, $\psi(x)$, to the location $x = 2^k.n$ and then dilating by a factor of 2^k. The function $\psi(x)$ is called the mother wavelet. The parameter, $2^k.n$, has the significance of localising the basis function at $x = 2^k.n$ and its neighbourhood. The space-frequency localisation feature of wavelet transform will be used for pattern recognition of the WIM signals.

2.3 Wavelet Basis

The wavelet basis used here for decomposition is shown in figure 1 and is represented mathematically by:

$$\psi(x) = \begin{cases} = -0.5 - \dfrac{(x+0.5)}{2} & ;-1.5 \le x < -0.5 \\ = 1.5 + 4x & ;-0.5 \le x < 0 \\ = 1.5 - 4x; & ;0 \le x < 0.5 \\ = -0.5 + \dfrac{(x-0.5)}{2} & ;0.5 \le x < 1.5 \\ = 0 & ;\text{otherwise} \end{cases} \quad (2)$$

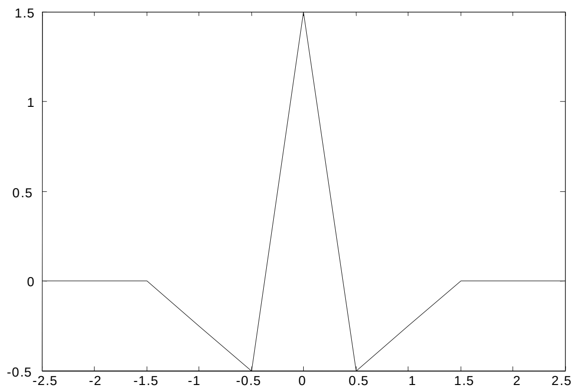


Figure 1 - Decomposition Wavelet Function ψ

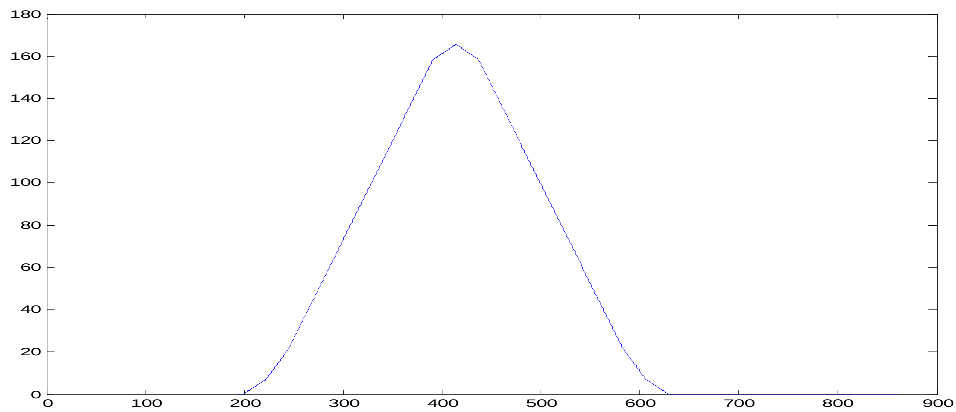
3. Application of the Wavelet Transform

A wavelet that detects underlying discontinuities in the slope of a noisy strain signal was required. The change in slope in the strain signal is generated where the axle arrives/departs the bridge and the times of axles crossing the sensor location. From the axle positions being identified accurately, the number of axles can be computed. The velocity of the vehicle can be found by repeating the procedure stated above at two positions along the bridge, and calculating the time taken for the axles to travel the known distance from one sensor location to the other. Different symmetrical wavelets were tested and the biorthogonal wavelet described above was found to give the most pronounced response to underlying changes in slope of the strain signal.

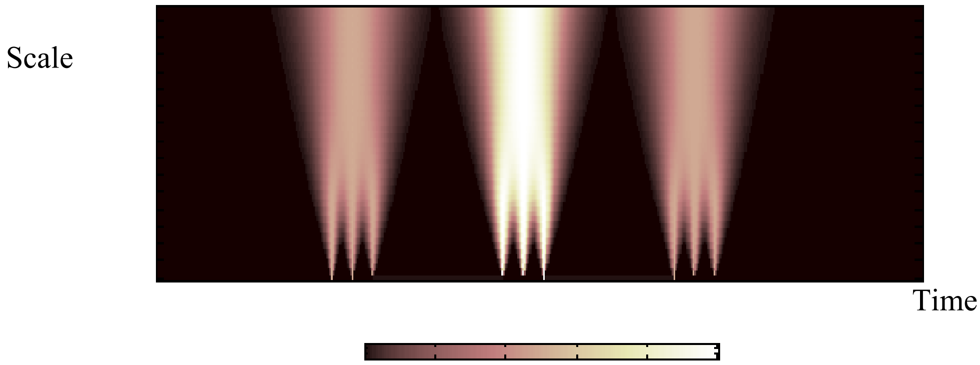
4. Results of Simulation Tests

The scale of a wavelet is the measure of how compressed or dilated the wavelet is when it is applied to the signal. The higher the scale of the wavelet, the lower the frequency. At high scales the wavelet will detect slowly changing underlying features of the signal while at the low scales the wavelet will pick out rapidly changing detail. The wavelet transform was applied to the theoretical strain response of a tridem and the resulting wavelet coefficients for a particular scale are shown in figure 2(c). The slope discontinuities, some of which are barely perceptible in figure 2(a), are represented by peaks in figure 2(c). As is evident from figures 2(c) and 3(b), convex changes in slope yield positive peaks in the wavelet coefficients and concave changes in slope yield negative peaks.

Figure 2(b) illustrates a contour plot of the wavelet coefficients for a tridem at different scales. At low scales the peaks are clearly visible while at higher scales the wavelet coefficients show that there is something happening at that point in the signal but it is not able to focus on the minor changes. To ensure accuracy in vehicle identification the choice of scale to be used is very important.

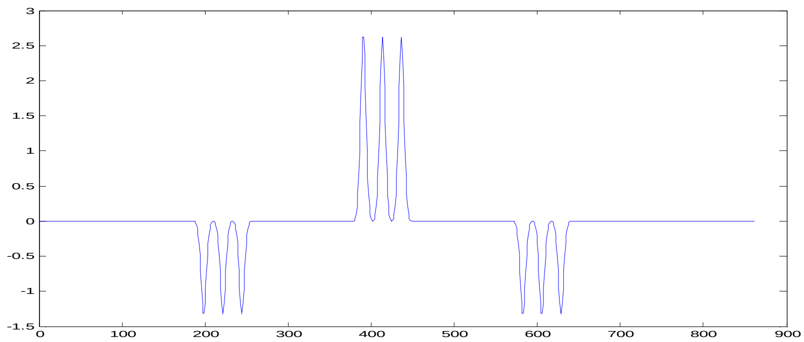


(a) Strain versus Time



Scale of colours from Min to Max

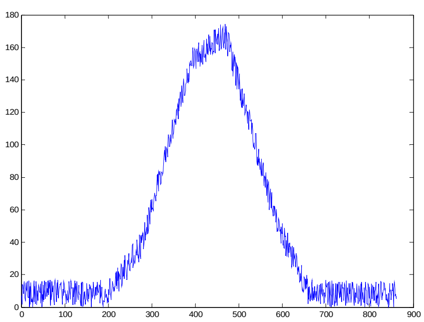
(b) Wavelet Coefficients $W(k,n)$ for a Tridem at Different Scales



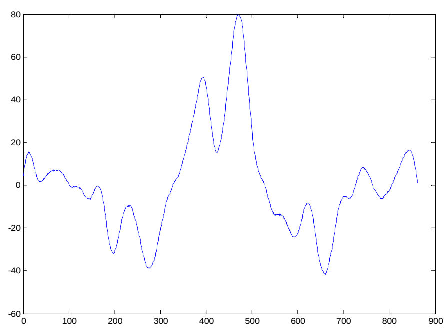
(c) Transformed Strain versus Time for Particular Scale

Figure 2 – Theoretical Strain Response for a Tridem Crossing Simply Supported Bridge

The choice of scale is especially important when the signal is noisy. Figure 3(a) illustrates the theoretical strain for a 2-axle truck with random noise of up to 10% of the maximum strain added to it. The corresponding wavelet coefficients for a particular scale are shown in figure 3(b). The peaks are still clearly visible and in the correct positions.



(a) Strain versus Time



(b) Transformed Strain versus Time

Figure 3 – Theoretical Strain for a 2-axle Truck with Random Noise of Up to 10% of the Maximum Strain Added to it

5. Experimental Test

Experimental strain data was obtained from a 30.5m long instrumented beam and slab bridge in Hrastnik, Slovenia. A photograph of the bridge and the positions of the strain gauges measuring the transverse bending can be seen in figure 4. It is a 2-direction bridge that was instrumented in both the longitudinal and transverse directions.

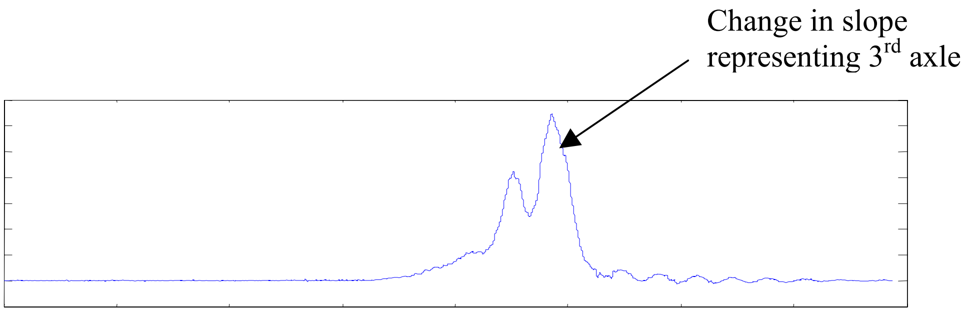
Figure 4 – Instrumented Hrastnik Bridge

The test was carried out with a 3-axle rigid truck and a 5-axle semi-trailer. The vehicle characteristics are presented in Table 1.

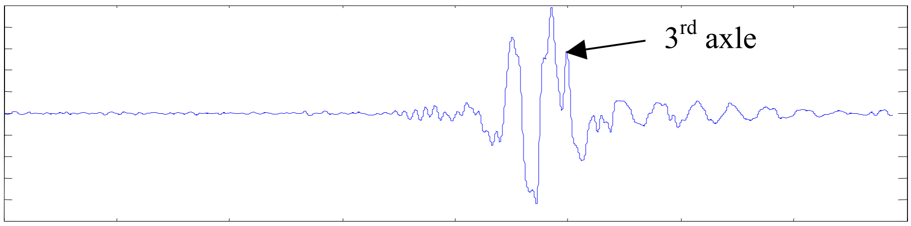
Table 1- Vehicle characteristics

		1	2	3	4	5
3-axle	Axle spacing (m)	3.2	1.34			
	Axle weight (kN)	50.6	76.5	74.6		
5-axle	Axle spacing (m)	3.6	3.02	1.32	1.32	
	Axle weight (kN)	71	87.7	59.6	55.1	59.1

The longitudinal strain measurements were unsuitable for NOR B-WIM due to the extent of bridge vibration. The 1st natural frequency is not close to the axle crossing frequency (bridge 1st natural frequency = 3.2Hz, which matches an axle travelling at 351km/hr). However, the magnitude of the vibrations was sufficient to significantly alter the static response. The measurements from the transverse direction however were a lot clearer. Examples of strain responses for the 3-axle and the 5-axle trucks and their corresponding wavelet transforms are in figures 5 and 6.

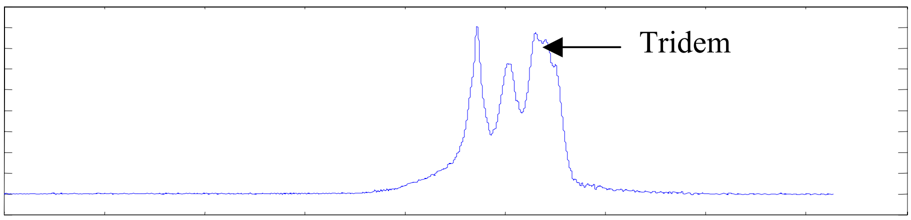


(a) Strain Response

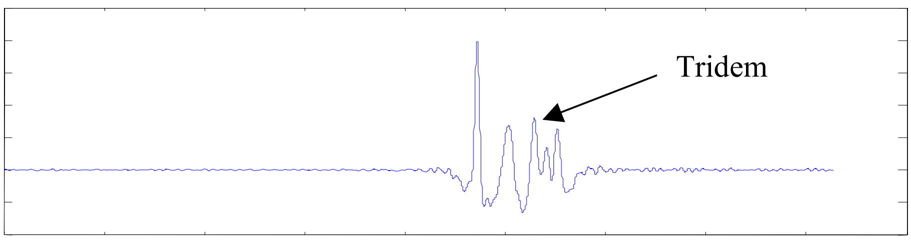


(b) Wavelet Transform

Figure 5 – Response to 3-axle Truck



(a) Strain Response



(b) Wavelet Transform

Figure 6 – Response to 5-axle Truck

The axles in the transformed function for the 5-axle truck are clearly visible. The wavelet transform accentuates the peaks where the axles occur. In the 3-axle case, the advantage of using the wavelet transform is also shown. The first and second axles are clearly visible in the raw strain signal but the third axle is only represented as a minor change in slope. The wavelet picks out this change in slope and emphasises it as seen in Figure 5(b).

Two runs of each truck were carried out in Lane 1. The spacing between the axles in number of scans were ascertained from the strain signals through the use of the wavelet transform. Table 2 shows the errors in the detection of the axle locations. The velocity in this case was calculated from axle detectors, as two transverse strain-measuring locations were not used. Errors may also have occurred from the vehicles accelerating or decelerating during the experimental procedure.

Table 2 – Errors in axle position in the strain data (m)

	3-axle(1)	3-axle(2)	5-axle(1)	5-axle(2)
1st-2nd axle	+0.123	+0.489	-0.063	+0.038
2nd-3rd axle	+0.28	+0.102	+0.084	-0.042
3rd-4th axle			-0.14	+0.093
4th-5th axle			-0.026	-0.092

The majority of the errors are below 10cm and the rest of the results are in the 10-50cm band. One result – 3-axle(2) – is quite poor showing that the approach does not guarantee high accuracy in all cases. However, the scope of this preliminary study is insufficient to draw definitive conclusions. The authors are confident that, with further development, such problems can be overcome or reduced in the near future.

6. Conclusions

This paper presents a wavelet-based approach to nothing on the road (NOR) Bridge Weigh-In-Motion (B-WIM). The strain gauges or transducers underneath the bridge are used to identify vehicle occurrences, velocities, numbers of axles and axle spacings without the use of axle detectors. Through the use of the wavelet transform, the vehicles' axle locations are found. It has been shown that the scale of the wavelet must be adapted to suit each strain case depending on the amount of noise in the signal to ensure accuracy in vehicle identification.

Acknowledgements
The author gratefully acknowledges the Slovenian National Building and Civil Engineering Institute (ZAG) and the Cestel company (http://www.siwim.com) for supplying bridge WIM data.

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MOVING FORCE IDENTIFICATION: PRACTICE AND REVIEW

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Abstract

Moving force identification from dynamic responses of a bridge is an important inverse problem in the civil and structural engineering field. Current knowledge on factors affecting performance of moving force identification methods is reviewed in this paper under main headings below: background of moving force identification, experimental verification both in laboratory and in field. Although there are still many challenges and obstacles to be overcome before these methods can be implemented in practice, some results serve as a good indicator to steer the direction of further work in the field.

Keywords: WIM, Moving Force Identification, Dynamic Responses, Practice, Review.

Résumé

L'identification des forces mobiles à partir de la réponse dynamique d'un pont est un problème inverse important en génie civil et des structures. Les connaissances actuelles sur les facteurs qui influent sur la performance des méthodes d'identification des forces mobiles sont passées en revue selon les principales rubriques : bases de l'identification des forces mobiles, vérification expérimentale en laboratoire et sur site. Bien qu'il restent de nombreux enjeux et obstacles à franchir avant que ces méthodes puissent être mises en œuvre en pratique, certains résultats donnent de bons indicateurs pour orienter les futurs travaux dans le domaine.

Mots-clés: Pesage en Marche, Identification des Forces Mobiles, Réponses Dynamiques, Révision.

移動載重辨識之回顧及應用

摘要：

利用橋梁之動態反應辨識移動荷重爲土木及結構工程學領域中一個重要的問題。本文主要回顧影響移動載重辨識系統績效之相關因素，包括：移動載重辨識之基礎發展以及在實驗室及現場之驗證工作。雖然在上述方法實際應用前仍有許多挑戰及困難，但部分已獲知之研究結果亦可做爲未來相關工作之參考。

關鍵字：動態地磅、移動載重辨識別、動態反應、實際應用、回顧

1. Introduction

Accurate and reliable data on the nature and extent of heavy vehicles use of both the road and bridge network, especially dynamic moving vehicle loads, is extremely important for pavement and bridge design (Stevens, 1987; Fryba, 1999). Most of the traditional ways mentioned acquire data could only measure static axle loads, and they are expensive and subject to bias, e.g. the Weigh-in-Motion (WIM) systems can only acquire static equivalent axle loads of a vehicle (Moses, 1978; Peters 1984&1986; Koniditsiotis et al., 1995). The dynamic load data are valuable not only to the design of bridges and pavements but also to their monitoring and retrofitting since the dynamic wheel loads might increase road surface damage by a factor of 2-4 over that due to static wheel loads (Cebon, 1987). Whittemore et al (1970) and Cantieni (1992) have separately described systems that use instrumented vehicles to measure dynamic loads on bridge deck. Unfortunately, the acquired data are also subject to bias. Over the past years, some great effort has been made for obtaining an advanced WIM technique, a series of moving force identification methods have been put forward, which can compute dynamic wheel loads with an acceptable accuracy (O'Connor and Chan, 1988; Chan et al., 1999; Law et al., 1997; Law et al., 1999), further these methods have been enhanced and merged into a moving force identification system (MFIS) (Yu, 2002). However, there still exist some limitations if these methods could actually be operated in practice (Chan et al., 2000). This paper tries to provide a review on current knowledge of the factors affecting the performance of moving force identification methods, as well as to find the right way to steer the direction of further work.

2. Background of Moving Force Identification

2.1 Models of Bridge-Vehicle System

The bridge-vehicle system is a very complicated system. The interaction between bridge and vehicle is a complex phenomenon governed by a large number of different parameters. The use of simplified models is more effective to establish a clear connection between the governing parameters and the bridge response than a complex model. Normally, the bridge decks are modelled as beams using either the *Beam-element model* (O'Connor and Chan, 1988) or the *Continuous Beam Model* (Bernoulli-Euler beam or Timoshenko beam) or modelled as plates (isotropic plates or orthotropic plates). The vehicles are modelled as a moving force, a moving mass (Lin and Trethewey 1990) or a moving oscillator (Pesterev and Bergman, 1997; Yang et al., 2000). Usually, a quarter-truck model, a half-single-unit two-axle truck model, and a half five-axle semi-trailer truck model developed by Todd et al (1989), or 3-D, 2-D, and single sprung mass (1-D) system (Chatterjee et al., 1994) are adopted.

2.2 Identification Methods

Four identification methods have been put forward, which can compute dynamic wheel loads with an acceptable accuracy. The interpretive method I (IMI, O'Connor and Chan, 1988) developed a system to measure the dynamic vehicle-bridge interaction forces from the bridge total responses caused by the inertial or D'Alembert's forces and the damping forces, in which the bridge deck is modeled as an assembly of lumped masses interconnected by massless elastic beam elements. The interpretive method II (IMII, Chan et al., 1999) was similar to IMI but used Euler's equation for beams to model the bridge deck in the interpretation of dynamic loads crossing the deck. The Euler beam theory together with modal analysis was used to identify moving loads from the bridge responses. The time domain method (TDM, Law et al., 1997) modeled the bridge deck as a simply supported Euler beam with viscous damping and the vehicle/bridge interaction forces was modeled as one-point or two-point loads with fixed axle spacing, moving at constant speed. The moving forces were then identified using the modal superposition principle in time domain. Further, the frequency-time domain method (FTDM, Law et al., 1999) performed Fourier transformation on the equations of motion which are expressed in modal co-ordinates. The relation between the responses and the moving forces was established first and the force spectrums were calculated by the least-square method in the frequency. The time histories of moving forces can then be obtained by performed the inverse Fourier transformation. These methods above have been enhanced and merged into a moving force identification system (MFIS) (Yu, 2002). The first method is developed based on the *beam-element model*, the others based on *continuous beam model*.

It is easy to find that most of the identification methods are eventually converted to a linear algebraic equation, such as, $Ax = b$. Where, x is the time series vector of the unknown time-varying moving force $P(t)$, b is the time series vector of the measured response of bridge deck. The system matrix A is associated with the bridge-vehicle system. In principle, the equation will have a solution given by the least-squares method, which be written as $x = A^{+} b = [(A^T A)^{-1} A^T]\, b$. Where A^{+} denotes the *pseudo-inverse* (PI) of matrix A. The solution vector x is called *PI solution*. This definition requires matrix A to have full rank. However, the matrix A is often rank deficient or close to rank deficient then A^{+} is best calculated from singular value decomposition (SVD) of matrix A (Lindfield and Penny, 1995). If matrix A is real, the SVD of A is USV^T, the solution can easily be calculated by $x = A^{+} b = [VS^{-1}U^T]\, b$, the solution vector x here is called *SVD solution*.

3. Experimental Verification in Laboratory

3.1 Experimental Setup

In order to evaluate the moving force identification methods, a series of experiments have been carried out in laboratory. As an example, a simply supported beam with a span of 3.678*m* long and 101*mm* by 25*mm* uniform cross-section is constructed, which made from a kind of mild steel with a density of $7335\, kg/m^3$ and a flexural stiffness $EI = 29.92\, kN/m^2$. Two kinds of model cars are also made to simulate two-axle vehicle and multi-axle vehicle respectively. One has two axles at a spacing of 0.55*m* and is mounted on four rubber wheels. The static mass of the whole car is 12.1*kg* with a rear axle of 3.825*kg*, its axle spacing to span ratio (ASSR) is 0.15. The other has three axles based on the AASHTO (1996) loading code. Two types of ASSRs, 0.15:0.15 and 0.15:0.20, are set, their corresponding axle load ratios are 2W:8W:8W and 3W:7W:7W respectively, the total weight of car is 18kg for the former case and 17kg for the latter respectively as W=1 *kg*. The model car was pulled by a string wound on the drive wheel of an electric motor in the front of the beam. Its speed can be adjusted to control and determine the car speed exactly. When the car traversed the beam bridge, the induced bridge responses were recorded simultaneously using strain gauges and accelerometers installed on the lower surface of the beam, and then used as input data for moving force identification.

3.2 Parameter Studies

Many parameters play an important role in the moving force identification; therefore it is necessary to study the effects of main parameters on the four identification methods. They are bridge-vehicle parameters, measurement parameters and algorithm parameters.

Effect of Bridge-Vehicle Parameters

Usually, a sufficient number of vibration modes of bridge must be included in the identification calculation. But, what is the sufficient number of modes? The answer depends not only on the characteristics of the bridge-vehicle system but also on the solution to the over-determined equation used in the moving force identification method. The IMI is independent of the mode number. The IMII needs at least the first three modes or more to correctly identify the two moving forces. For both the TDM and FTDM, the minimal necessary mode number required is 4. If the first five modes are used to identify the two moving forces, the identification accuracy is the highest in the cases studied (Chan, Yu et al., 2000). Generally, the mode number involved should be bigger than or at least equal to one more than axle number of vehicle.

Vehicle speed plays an important role for the dynamic behavior of a bridge subjected to loads moving across the bridge (Fryba, 1999). It is interesting to notice that the identification accuracy first increase and then decrease with increase in car speed for the IMI. But it is not so significant for both IMII and TDM. It may be concluded that both IMII and TDM are independent of car speeds. Anyway, the IMII is more suitable for the higher vehicle speed. The TDM can effectively identify the forces in all the speed cases. The faster vehicle speed is also of benefit to both the TDM and FTDM, and unfortunately, the FTDM fails in the lower speed cases if PI solution is used to solve the equations (Chan et al., 2001b). However, when using the SVD solution the situation is completely changed, it makes the FTDM from original ineffective to effective and it shows the FTDM has a better identification accuracy in the fast speed as well (Yu and Chan, 2003).

In reality, heavy vehicles mainly comprise articulated and nonarticulated vehicle frames. Previous research using analytical model has shown that nonarticulated vehicles generate much higher vibration on the bridge compared to articulated vehicles (Chan and Yung, 2000). The three-axle vehicle models are allowed to switch from articulated to rigid connection, i.e. nonarticulated connection between tractor and the semi-trailer by two fixed studs in the laboratory. The results show that the identified multi-axle vehicle loads are reasonable and acceptable for both the articulated and nonarticulated vehicles. The moving force identification system can correctly identify the multi-axle vehicle loads even if the middle axle of the nonarticulated vehicles is hanging in the air (Yu and Chan, 2004).

Three types of suspension systems are incorporated in the vehicle models. They are rigid connection, sprung connection, and pre-compressed sprung connection between vehicle frame and axle respectively to simulate different suspension systems. The results show that the suspension systems make an obvious impact on both dynamic characteristics of vehicles and identification accuracy. The fundamental frequency of vehicles is significantly changed with different suspension systems. It is evidently beneficial to the improvement of identification accuracy when the nonarticulated vehicles are suspended and provided with more suspension systems (Yu and Chan, 2004).

Effect of measurement parameters

The effects of sampling frequency using the IMI and IMII are not too obvious within 333 Hz, but after this range, the effects become more significant even make the two methods failure at sampling frequency 1000 Hz The TDM is suitable for the higher sampling frequency. The effect of sampling frequency on the FTDM increases as the sampling frequency, and the FTDM fails if the sampling frequency is higher than 333 Hz and PI solution is used (Chan, Yu et al., 2000). However, the use of the SVD not only makes the FTDM method effective but also results in good identified results with higher accuracy, whereas direct calculation of the PI solution causes the identification method to fail (Yu and Chan, 2003). Moreover, both the TDM and FTDM have higher identification accuracy than both the IMI and IMII.

Measurement stations affect the identification accuracy. For the IMI and IMII, the required numbers of stations can be determined referring to the references (O'Connor and Chan, 1988; Chan et al., 1999). For the TDM, it requires at least three stations to obtain the two moving forces correctly. The FTDM should have at least one more measurement station than using the TDM, i.e., 4. In addition, the FTDM is sensitive to the locations of measuring station, which should be selected carefully when the PI solution is adopted (Chan, Yu et al., 2000). Once the SVD is used for the FTDM, the identified results are acceptable and achieve a very high accuracy even they exceed the acceptable accuracy range when using the PI solution in all the study cases. It is predicted that the identification method is independent of the measurement stations if the SVD method is adopted (Yu and Chan, 2003). In general, the identification accuracy is better if more measuring stations are adopted for both the TDM and FTDM, but it will take longer computational time.

Effect of algorithm parameters

Usually, the SVD technique applies a variant of the QR algorithm to reduce the super-diagonal elements to a negligible size and to result in a diagonal form through an iteration procedure. Here, a given tolerance parameter, i.e. *epsilon* ε, should be set as a criterion related to rejecting or accepting of zero singular values. The criterion may depend on the accuracy of the expected results and, in practice, may be difficult to establish. Results show that a smaller tolerance parameter ε is beneficial to moving force identification. However, if ε is too small the computation cost (CPU) is higher because it need more iteration times for convergence. In addition, the SVD technique increases the CPU time by 60% as compared to that for the PI solution. It is too expensive and not beneficial to the real-time analysis in situ. To take account of all the above aspects at the same time, ε value set to be 1.0e-6 for study cases is appropriate (Yu and Chan, 2003).

The identified results are noise sensitive and they exhibit fluctuations at the beginning and end of the time histories. These moments correspond to the change in the vibration state, vice versa, and the solutions are ill-conditioned. A regularization method developed by Tikhonov and Arsenin (1977) can be introduced to provide bounds to the solution (Law et al., 2001). The results obtained are greatly improved over those without regularization. The TDM is found better than the FTDM in solving for the ill-posed problem. Both simulation and laboratory test results indicate that the total weight of a vehicle can be estimated indirectly using moving force identification methods with some accuracy at least with FTDM (Law et al., 2001).

3.3 Evaluation of identification methods

When a model car traversed the model bridge constructed in laboratory, the induced bridge responses at stations were recorded first and then input into the moving force identification system. Any methods in the system can be chosen to identify the moving axle loads, which are used to reconstruct the so called "rebuilt" responses of bridge. The relative percentage error (RPE) between the measured and rebuilt responses is adopted to assess the efficiency and robustness of identification methods. Table 1 gives a comparison between RPE values when different identification methods are used to estimate the two moving axle loads from measured bending moments at seven measurement stations, here, L denotes the beam span length. It shows that all the RPE data are lower than 10% except at the first station ($L/8$) and 7th station ($7L/8$) for IMII method. This illustrates that all the four identification methods involved in the moving force identification system are correct and effective. Moreover, the results from both TDM and FTDM are clearly better than ones from both IMI and IMII. Further, the results provided by SVD solution are better than ones by PI solution, particularly for FTDM. It shows SVD technique can improve the identification accuracy.

Table 1 – Comparison of identified results

Method	RPE (%)						
	***L*/8**	**2*L*/8**	**3*L*/8**	**4*L*/8**	**5*L*/8**	**6*L*/8**	**7*L*/8**
IMI	9.37	9.51	9.73	9.62	9.55	9.14	8.36
IMII	12.2	6.00	6.98	4.40	6.05	5.75	13.2
TDM	5.42 5.43	3.08 3.09	1.80 1.80	2.58 2.56	1.95 1.94	3.44 3.43	4.83 4.83
FTDM	5.74 4.53	2.80 2.52	2.15 1.87	2.08 1.95	2.14 1.82	2.41 2.24	4.74 3.17

Notes: The undervalued values are from SVD solution, others from PI solution.

4. Experimental Verification in Field

Before the field measurements, a moving force identification method taking into account the effects of prestressed concrete bridge is presented (Chan and Yung, 2000a) based on IMI method. A 2-axle medium lorry is modeled as a set of forces, with their magnitudes either constant or time-varying, moving across a bridge model with a span length of 28 m. Results show that identified forces are identical to input forces only when no noise is added to the simulated bridge responses. The identified forces from responses which include noise are poor, even with a noise level as low as 1%. However, the identification can be greatly improved using a low-pass filter. Results also show that the identified forces are over- and underestimated, respectively, when the prestressing effects are neglected in the identification and calibration processes. Large errors are also obtained when the prestressing effects are neglected in both processes. Additionally, the errors decrease with decreasing prestressing forces, and do not change with the magnitude of axle forces and mass per unit length.

As an extension work of above theory (Chan and Yung, 2000a), field measurements were carried out to verify the proposed method in October 1995 on an existing prestressed concrete bridge of Ma Tau Wai Flyover, Hunghom, Kowloon, Hong Kong (Chan, Law et al., 2000). A two-axle heavy vehicle of 15 tons was hired for the calibration test of the field measurements. The dynamic bending moments of the test bridge deck brought about by both hired one and in-service 77 vehicles were acquired respectively. Dynamic axle forces were identified by means of the TDM method. The equivalent static axle loads of the two cases are tabulated in Table 2, which shows that the gross weights of both Test 2 and Test 3 are acceptable with percentage differences of 3.69% and 0.85% respectively (COST323, 1999). After obtaining the identified two axle loads of the control vehicle, the rebuilt bending moment responses can be calculated based on the forward problem, and then the RPE data between the measured and the rebuilt responses at each channel can be estimated as list in Table 3 for the control vehicle. Since no information was available for the axle loads of the in-service vehicle, the accuracy of identified dynamic axle loads was also studied using only RPE between the measured and rebuilt responses. Results show that the axle loads can be identified with acceptable results for both hired and in-service vehicles. Therefore the proposed method is valid for identifying dynamic axle forces. Gross weights can be obtained by summing up the equivalent axle load of each axle.

Table 2 - Summary of equivalent static loads identified with considering prestressing

Test case	Axle 1		Axle 2		Total	
	Equivalent static load (kN)	Difference (%)	Equivalent static load (kN)	Difference (%)	Gross weight (kN)	Difference (%)
2	65.22	1.97	91.22	4.95	156.44	3.69
3	62.48	-2.31	89.69	3.19	152.17	0.85

Table 3 - Summary of RPE between responses for control vehicle

Test case	RPE (%)				
	Ch.2	Ch.3	Ch.4	Ch.5	Ch.6
2	2.12	3.13	2.74	9.82	7.31
3	5.87	9.96	3.96	2.38	6.40

5. Conclusions and Recommendations

Recent advances on identification methods of moving loads identified from bridge responses are reviewed in this paper. The background of moving force identification is introduced. Numerical simulations, illustrative examples and comparative studies on the effects of different parameters on the system have been carried out and critically investigated. Bridge-vehicle system models have also been fabricated in the laboratory to validate the correctness and robustness of the proposed methods involved in the moving force identification system (MFIS). Field measurements have also conducted to assess the applicability of the methods in practice. The results show that all four identification methods involved in the MFIS can effectively identify moving axle loads on bridges and can be accepted as practical methods with higher identification accuracy. However, there are still many challenges and obstacles to be overcome before these methods can be implemented in practice, further studies on the moving force identification are necessary and recommended based on the previous experiences and results:

- Although the moving force identification methods are developed and have been proved to be successful, the work mainly focused on laboratory studies. Further field work is necessary and recommended to validate the methods and to accommodate them to practical bridge-vehicle system in engineering.
- Present research is mainly based on the measured bending moment responses induced by the passage of vehicles on bridges; however, other types of bridge responses, especially for acceleration responses easy to measure and operate, should be used to identify the moving loads on bridges. In the cases, a higher sampling frequency, more measurement stations and mode numbers are recommended to adopt in the calculation of identification.
- It is always recommended to use the SVD solution instead of the PI solution, especially for the frequency-time domain method. However, performing a full-SVD is too expensive in practical application. An algorithm to compute a partial SVD may be used instead (Vogel et al., 1994), or replacing the full-SVD by a RRQR factorization (Bazan et al., 1996). The fast computing method and powerful computer is necessary for real time computation and some techniques of splitting the larger coefficient matrix into smaller sub-matrix are recommended in order to make the computation more cost effective.
- Moving force identification from bridge responses is a typical inverse problem tends to be ill-conditioned, in which the effects of errors are of major concern. Numerical scaling and regularization techniques are needed to improve ill-conditioned effects (Stevens, 1987). However, finding the optimal regularization parameter λ is the main difficulty of applying the regularization technique, S-curve (Busby and Trujillo, 1999), L-curve (Hansen, 1992), and GCV methods (Zhu et al., 2002) can be used but subjected to researcher's experiences and prior information.
- The central difference, Newmark-β and Wilson-θ methods are often used in the moving force identification process, the measurement errors are easy to be amplified and spread abroad, the precise time-step integration technique (Zhong et al., 1994) may be used to establish a calculation format between responses of bridges and moving loads on bridges for more accurate results, especial for both IMI and IMII methods.

Acknowledgements
The project is supported by National Natural Science Foundation of China (50378009) and The Hong Kong Polytechnic University Postdoctoral Fellowship Research Grants (G-YX25).

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WEIGH-IN-MOTION RESEARCH AND DEVELOPMENT ACTIVITIES AT THE OAK RIDGE NATIONAL LABORATORY





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Abstract
The Oak Ridge National Laboratory (ORNL) has been involved in Weigh-in-Motion (WIM) Research with both government agencies and private companies since 1989. The discussion here will focus on the United States Army's need for an automated system to weigh and determine the center-of-balance for military wheeled vehicles as it relates to deployments for both military and humanitarian activities. A demonstration test at Fort Bragg/Pope AFB of ORNL's first generation portable Weigh-in-Motion (WIM Gen I) will be discussed as well as the development and fielding activities for a WIM Gen II system.

Keywords: Weigh-In-Motion, WIM, Center-of-Balance, Defense Deployments, Aircraft Load Planning.

Résumé
Le laboratoire national d'Oak Ridge (ORNL) a été impliqué dans la recherche de Peser-dans-Mouvement (WIM) des organisms gouvernementaux et des entreprises privés anonymes depuis 1989. La discussion ici se concentrera sur le besoin de l'armée des Etats-Unis d'un système automatisé de peser et déterminer le centre de l'équilibre pour les véhicules roulés militaires pendant qu'elle se relie aux déploiements pour des activités militaires et humanitaires. Un essai de démonstration au fort Bragg/Pope AFB du Peser-dans-Mouvement portatif de la génération d'ORNL (la GEN de WIM I) sera discutée comme le développement et les activités fielding pour un système de GEN II de WIM.

Mots-clés: Peser-dans-Mouvement, WIM, Centre-de-équilibre, Déploiements de la Défense, Planification de Charge D'avion.

OAK RIDGE 國家試驗室之動態地磅研究現況

摘要：
自 1989 年起 Oak Ridge 國家試驗室 (The Oak Ridge National Laboratory, ORNL) 即與政府機關以及私人公司投入動態地磅 (Weigh-in-Motion, WIM) 之相關研究。本文內容將著重於美國陸軍對於可自動量測及決定軍用車輛重心位置系統之需求進行討論，該系統並可同時用於軍事調度以及人道救援行動中。本文將針對 ORNL 第一代可攜式動態地磅系統 (WIM Gen I) 於 Bragg/Pope 空軍基地之實地測試進行說明，並同時描述第二代可攜式動態地磅 (WIM Gen II) 之發展以及實地應用情形。

關鍵字：動態地磅、重心、防禦調度、航機載重規劃

1. Introduction and Background

The United States Department of Defense must maintain the capability to rapidly project massive combat power anywhere in the world with minimum preparation time. Currently, personnel use portable individual wheel weight or fixed in-ground static scales, tape measures and calculators to determine vehicle axle weights, total vehicle weight and center-of-balance for vehicles and palletized cargo to be shipped via railcar, sealift, or airlift in support of military and humanitarian operations. The process of manually weighing and measuring all vehicles and cargo subject to these transshipment operations is time-consuming, labor-intensive, and most importantly is prone to human errors that can result in safety hazards and inaccurate data.

Errors can result from inaccurate or incomplete identification of vehicles and equipment; misreading a scale or tape measure, manually recording data incorrectly; manually miscalculating the axle weight, total vehicle weight or center-of-balance; and transferring data from manually prepared work sheets into an electronic database via keyboard entry personnel. Many of these errors can greatly increase during stressful deployment times and adverse weather conditions.

Errors in determining weighs and balances in military deployments as well as commercial air transport can be fatal. In June 2002, a special operations combat supply plane crashed in Afghanistan, killing several of the crew. U.S. Air Force accident investigators concluded that the crash was caused by “imprecise information” about cargo weight combined with a “get the job done” attitude. The aircraft crashed not because it was overloaded but because it was overweight for the location, 7,200 feet above sea level. *Army Times* reported that weighing cargo at such isolated airstrips was not practicable —the Air Force special operations crews were relying instead on weight estimates (Rolfsen, 2002).

A Weigh-in-Motion (WIM) system may also have applicability in response to the National Transportation Safety Board’s February 2004 recommendation that federal regulators and the airlines develop methods to weigh passengers and baggage to prevent overloading of airplanes (Levin, 2004). The safety board had concluded that the crash of Air Midwest Flight 5481 on January 8, 2003, was caused by too much weight in the rear of the aircraft combined with a maintenance mistake. The United States military has recognized and documented a need for WIM technology (Keane, 1996) and further documented the requirement (Coats, et al., 2004a) and a recommended WIM technology solution for military applications in 2004 (Coats, et al., 2004b).

In this paper, we will concentrate on the military applications of WIM. We will discuss specific aspects of the United States Army/Oak Ridge National Laboratory WIM program which will include the discussions of: 1) a Fort Bragg/Pope Air Force Base (AFB) demonstration test where a first generation WIM prototype system WIM Gen I was compared to existing techniques for determining weighs and balance using fixed in-ground scales, single wheel weigh scales, tape measures, and calculators, 2) the present WIM-GEN II development program, as well as 3) testing and future plans.

The lack of a standardized airlift-weighing system for joint service use also creates redundant weighing requirements at the cost of scarce resources and time. The process of determining the vehicle weight, center-of-balance, and individual axle weights for load planning and assets visibility consists of: staging and identifying the vehicle; determining the individual wheel weights; determining the axle spacing; calculating the total weight, center-of-balance and individual axle weights; marking the vehicle with its total weight and center-of-balance; accumulating the vehicle data for a group of vehicles; and finally entering the data into an electronic database to enhance military planning and visibility capabilities. Presently, the entire process is performed manually using a large static truck scale or multiple individual portable wheel weight scales, tape measures, calculators, and clipboards. The process is very time consuming, manpower intensive and prone to human errors. The WIM system can greatly reduce the time required to perform this operation and eliminate the human errors resulting from the manual nature of these measurements, calculations, and data input.

2. Field Prototype Demonstration

The demonstration of the WIM was conducted at Fort Bragg/Pope AFB, NC in May 2003.

2.1 Purpose

The purpose of the WIM Field Demonstration was to provide analytical data that allowed the comparison of two existing weigh/center-of-balance determination techniques of weighing and determining the center-of-balance of military vehicles to a portable WIM Gen I system. The portable WIM Gen I system used during the comparison test was developed by the Oak Ridge National Laboratory for the United States Air Force Productivity, Availability, Reliability, and Maintainability (PRAM) office. The WIM Gen I was developed as a prototype WIM system to demonstrate the feasibility of the WIM concept in 1996. The WIM Gen I prototype system, funded by the PRAM office, was completed, calibrated and tested some years ago. At that time, additional funding was not provided to move the WIM Gen I forward from its prototype status to an improved harden commercially available WIM system to meet the needs of today's military. The results provided analytical data to show: 1) how the WIM Gen I system automatically determines the total vehicle weight, center-of-balance measured from the front axle, and the individual axle weights for military conventional single and dual wheeled vehicles as they move across the transducers at low speeds in real-time; 2) how automated processing significantly reduces the time needed to determine total weight, balance, and axle weights of unit vehicles; 3) how WIM avoids the class of errors (transcription and calculation) introduced through the current manual process; 4) how WIM reduces the required manpower to setup and operate the process, and 5) what enhancements were required to fully satisfy Army 's WIM requirements.

2.2 Description of Deployment Weighing Comparison Techniques

Three techniques for weighing and determining the center of balance for military vehicles were compared: 1) Large in-ground static truck scale (available at large power projection facilities), 2) Six to eight portable single wheel weight scales and 3) WIM Gen I system. Twenty-three vehicles and one container were used to test each technique. The data presented will focus only on the weighing process. Figure 1 illustrates temporally the procedure as it applies to the WIM and single wheel weight techniques. The static scale procedure is not included in the figure due to sheer simplicity (and immobility). The static scales are the most accurate and are as labor intensive in terms of the manual calculations (average total time - 4mins 48secs) as the single wheel weight scales (average total time – 4min 52 secs). Each weighing technique is explained in detail below:

A. In-ground Static Scales

1. Obtain and record the vehicle identification,
2. Pull the vehicle front axle onto the static scale, have the driver exit the vehicle, and manually record the front axle weight on the standard data sheet,
3. Pull the first and second axle onto the static scale, have the driver exit the vehicle, and determine the total weight of axle 1 and axle 2 combined; subtract the weight of axle 1 from the total weight of axles 1 and 2 to determine the weight of axle 2 and manually record the calculated weight,
4. Pull the third axle onto the scale and determine the total weight of the three axles; subtract the weight of axles 1 and 2 and record the resultant weight of axle 3,
5. Repeat step 3 until all the axle weights have been determined,

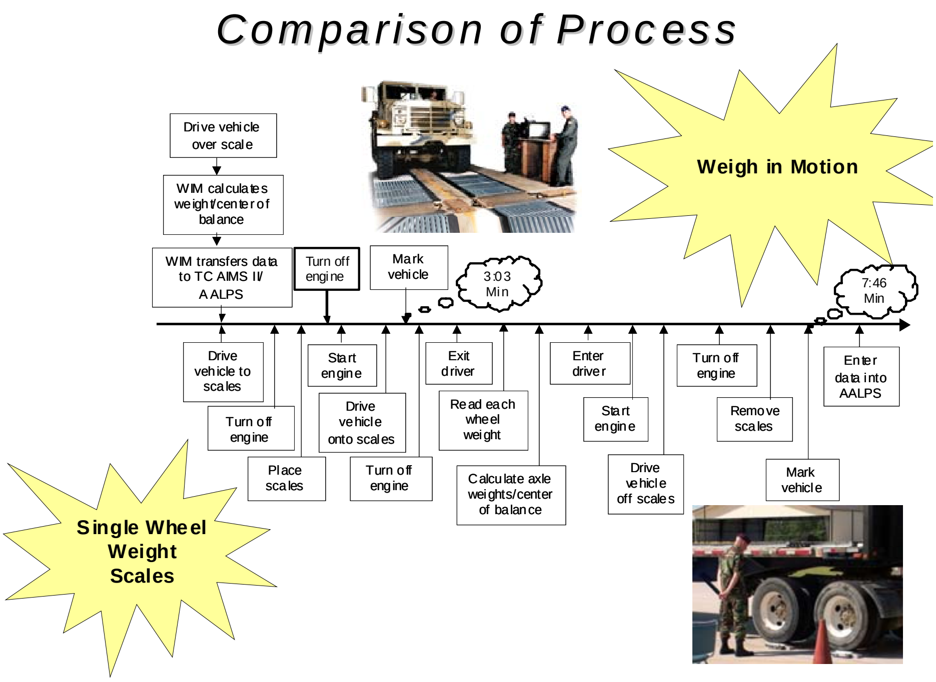

Figure 1 - Comparison of Process

6. Use a tape measure to measure and record the distance from the front forward edge of the vehicle to the center of axle 1,
7. Repeat step 6 for each of the axles,
8. Calculate the moment for each axle by multiplying the individual axle weight times the distance from the front forward edge to the individual axle,
9. Repeat step 8 for each axle,
10. Determine the total moment about the front forward edge by summing the individual moments for the individual axles.
11. Divide the total moment about the front forward edge by the total vehicle weight to determine the vehicle center of balance for the total vehicle, and finally
12. Transfer all weight and center of balance data for all the vehicles in the group manually to a hand written spreadsheet.

B. Portable Individual Wheel Weight Scales

1. Obtain and record the vehicle identification,
2. Pull vehicle into weighing position,
3. Position scales in front of the individual tire sets,
4. Pull the vehicle forward to position it in the center of each of the individual scales, set the brake, turn off the vehicle, and have the driver exit the vehicle,
5. Manually record the individual wheel weights,
6. Manually calculate and record the individual axle weights,
7. Measure and manually record the distance from the front bumper to axle 1,
8. Measure and manually record the distance from the front bumper to axle 2,
9. Repeat step 8 for each of the remaining axles,
10. Calculate and manually record the center of balance,
11. Transfer all weight and center of balance data for all the vehicles in the group manually to a hand written spreadsheet.

C. WIM GEN I System

1. Obtain and enter the vehicle identification into the WIM computer,
2. Instruct the diver to pull forward over the WIM system at a constant speed of 3-10 mph,
3. WIM system will automatically determine the individual wheel weights, individual axle weights, total vehicle weight, vehicle center of balance from the front axle and add the data to the group's data base,
4. Once weight and center of balance for all the vehicles in the group have been determined, the WIM system automatically accumulates and compiles the database,
5. Save the unit's database on appropriate storage media for input into electronic database.

The demonstration test photos in Figures 2-4 illustrate each of the three techniques. The military vehicles used in the test included a HMMWV, a 5-ton wrecker, a tractor with a flatbed trailer, a 5-ton vehicle with a trailer, and a forklift as well as a containerized load. The group of vehicles were prepared for deployment three times: first using an in-ground static scale, tape measure, a standard data sheet, and a calculator following standard military procedures; second using individual wheel weight scales, tape measure, a standard data sheet, and a calculator following standard military procedures, and; finally using the WIM Gen I prototype system.

Figure 2 - In-Ground Static Scale

Figure 3 - Individual Single Wheel Weight Scales

Figure 4 - WIM Gen I System

2.3 Results and Conclusions from the Current Deployment Weighing Comparison

The static scale and tape measure technique used three operating personnel; the individual wheel-weigh scales and tape measure technique used seven; and the WIM system used three. Figure 5 shows a plot of the average times for processing vehicles with varying number of axles as well as the overall scatter in the data.

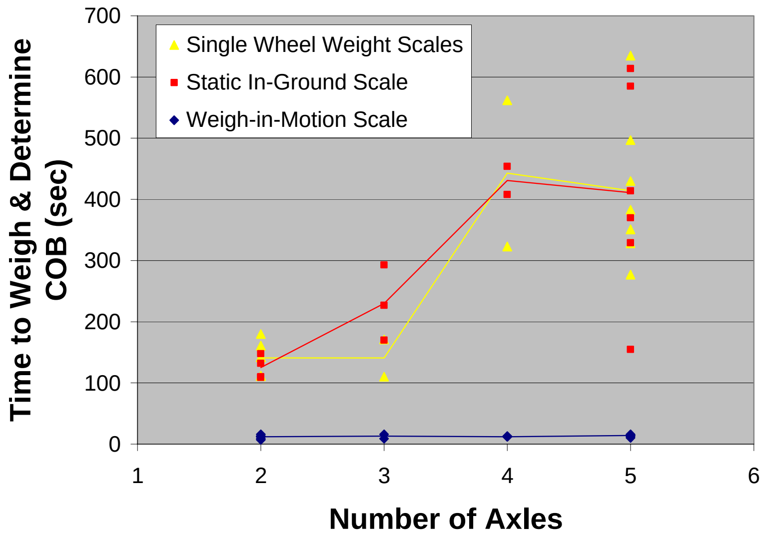

Figure 5 - Individual and Average Time Required to Weigh and Determine the Center-of-balance

Because of the manual nature of the weighing process (using both the static in-ground scale and the single wheel weight scales), the time required to complete the task tend to increase as the number of axles increase. Additionally, the variability in the task completion time increases as the number of axles increase. The WIM system consistently registered the same times, regardless of the number of axles.

The results from the static scale and tape measure technique were erroneous in 9% of the cases (due to human errors in the calculations); 14% for the individual wheel-weigh scales and tape measure technique; and 0% for the WIM system. The tests were performed in excellent weather conditions, but in rain, snow, high winds or other stressful environments, the human error rate would be expected to increase when using the two manual techniques.

The main advantage of the portable WIM is the reduction of potential errors along with a reduction in the level of effort. The individual wheel-weigh scales and the static scales require the transfer of data from a manually created data sheet to an electronic military planning system, as well as the manual calculation of individual axle weights, total vehicle weight and center of balance. The WIM system eliminates the need for manual calculations and feeds the data directly into other systems for the automated management of deployment and load planning. WIM also frees up military personnel to perform other deployment tasks.

3. Weigh-In-Motion Generation II Development Program

The accuracy demonstrated with the WIM Gen I prototype system was +/- 3%, based on 500+ vehicle passes of the standard weight-range of military vehicles. There were a number of advanced programs, technology improvements and lessons learned considered as a precursor to the development of WIM Gen II (e.g., Federal Highway Administration High Speed WIM and Air Mobility Battle Laboratory In-ground Static Scale Conversion to WIM projects). These experiences, along with the after action report from the comparison tests, influenced the technical path forward and resulted in a 66% accuracy improvement. Furthermore, ORNL’s experiences identifying and monitoring vehicle asset movements (Coats, et al., 2004b) were factored into the technical path forward strategy.

3.1 Overview

The WIM Gen II development focused on improving accuracy, automatic vehicle and cargo identification and providing an interface to load planning/deployment databases. Specific enhancements included improved weight and center-of-balance determination algorithms, on-board processing, modifications to simplify field operation, incorporation of state-of-the-art load cell transducers and electronics as well as optimal transducer spacing. Moreover, the WIM Gen II provides an enhanced field-ruggedized system that can go anywhere to automatically identify vehicle, cargo, weight/center-of-balance parameters safer and faster to all authorized systems and users, and be transportable in the back of the last vehicle to be loaded.

3.2 Weigh-in-Motion Generation II Design Features

The automated nature of the WIM Gen II system avoids the introduction of human errors caused by manual computations/data entry and minimizes the effect of adverse weather conditions and stress. Individual vehicles can be weighed continuously at low speeds (approximately 3-10 mph), at intervals of less than one minute and requires only two men to operate. Figure 6 shows the WIM Gen II system both assembled and disassembled. The system is comprised of 1, 2, 3 or 4 sets of transducers each with its own on-board processor, a power supply/host computer box, a wireless handheld tag reader/system display, wireless printer and a single cable (with links to daisy chain the transducer pads together). The system is designed to simplify setup by allowing the transducer pads to be positioned in any order while the host computer will determine their locations transparently. These enhancements allow vehicles to pass over the WIM system in either direction while the host computer provides all pertinent vehicle characteristics. The system operates in either the dynamic mode or static mode (i.e., individual wheel and axle weights are measured statically) in areas where WIM surface conditions are not available.

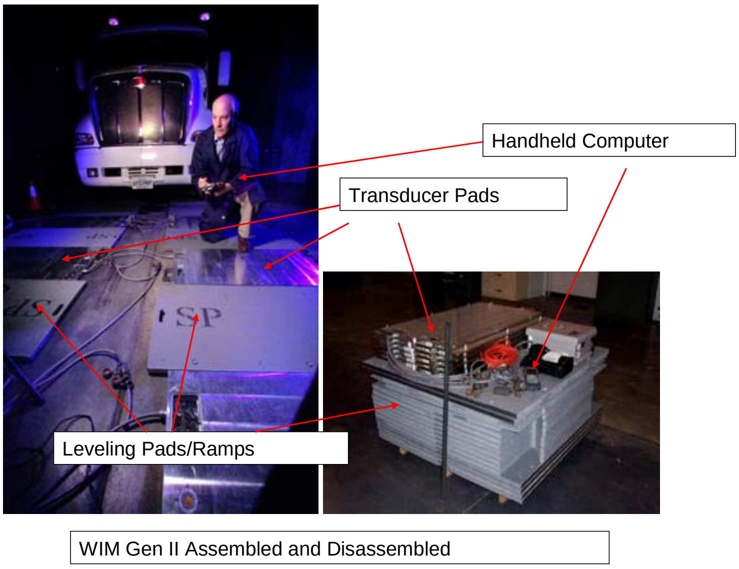

Figure 6 - WIM Gen II System Assembled and Disassembled

The WIM Gen II system's portability combined with the capability to rapidly weigh vehicles and determine their center-of-balance fully supports the rapid and safe deployment of equipment. For example, deploying and supporting units can set up their portable WIM Gen II systems at home stations, ports of embarkation, intermediate staging bases, ports of debarkation, theater staging bases, and austere airfields in accordance with the combat, combat support and combat service support requirements of the geographic combatant commander. Moreover, WIM Gen II enables timely distribution of real-world "actual" data electronically into external systems such as the Automated Air Load Planning System (AALPS). AALPS provides for load planning and manifesting purposes which feeds into the Transportation Coordinators' Automated Information for Movement System II (TC-AIMS II) for in-transit visibility to support operational planning, deployment and execution purposes.

3.3 Testing

Initial testing of the system has been undertaken. All the features outlined above have been verified and preliminary data indicate that the accuracy requirement of +/- 1% is feasible. Efforts in FY-05 are concentrating on rigorous testing of the system with a wide variety of private, commercial and military vehicles. Statistical design of experiments will be performed under a variety of surface conditions to determine the effect of the surface on system accuracy. Testing is being performed using all four sets of pads to determine how the accuracy varies with the number of pads in the system. Our goal will be to meet the accuracy requirement with a minimum number of pads thus reducing the system cost, physical size, weight and total number of components. This effort also includes integration of currently available commercial technology (e.g. Radio Frequency Identification (RFID) vehicle identification tags, bar codes, bar code readers).

3.4 Additional WIM Gen II Activities

Additional FY-05 activities include a limited production of systems to be delivered to sponsors for test and evaluation. The systems will be used in operational scenarios to emulate actual deployments prior to conveyance loading in a variety of physically diverse environments. Operating units will provide feedback on ease of use, ease of setup and tear down, any operating or maintenance problems encountered, as well as recommendations for improvements. As feedback is received, modifications to both hardware and software will be incorporated into the system where possible.

A cubic measuring system is being developed and incorporated into the WIM Gen II system to profile the vehicle and determine its height, width and length for loading and planning purposes (so-called cubic measuring technologies). ORNL is prototyping available cubic measuring technology and leveraging its own version of cubic measurement using digital technology. The goal is to determine if either of these technologies can be a potential solution for incorporating cubic measurement into a WIM system in an austere environment scenario. To achieve this goal it will be necessary to determine the technical developments necessary to provide a man-portable measuring system and provide this information electronically to down stream load planning systems such as AALPS and TC-AIMS II.

ORNL will upgrade fixed-site scales to dual use (static and dynamic) WIM scales at multiple selected sites and modify interface software to static weight scales for collection and processing of data. These systems would provide a user interface identical to the portable WIM Gen II system and utilize the same wireless handheld tag reader/system display.

4. Conclusions

The technologies described herein leverage COTS hardware components and custom developed software that has been demonstrated to: track and locate vehicles and cargo on a worldwide basis, provide the source data for In-transit Visibility and Total Asset Visibility in real-time, extract total vehicle and cargo weight, weigh individual surface contact for each tire, weigh individual axle, locate axle position, and calculate center-of-balance. The outputs of the WIM system are provided seamlessly to appropriate logistics planning systems and are subsequently made available to the global transportation network(s). An important and direct tangible benefit of WIM is the result of improved safety and labor savings.

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SUMMARY OF SESSION 1 : WIM TECHNOLOGY AND TESTING

Barbara K. Ostrom is a Principal Engineer at MACTEC Engineering and Consulting, Inc. She has been involved in the Long-Term Pavement Performance Program in traffic data collection, review and storage and user support of LTPP data since 1992. Prior to that she lead the Traffic Forecasting Section of the Maryland State Highway Administration. She holds BS and MS degrees in Civil Engineering from the Massachusetts Institute of Technology.

Raid Karoumi, born 1964, received his M.Sc. degree in Civil Engineering in 1990 and his Dr. Techn. degree in 1999 from the Royal Institute of Technology in Stockholm. Between 1990 and 1993 he worked as a consultant and was involved in a variety of special projects. His main interest is traffic load effects and dynamics of bridges. Raid is also in charge of several large research projects on instrumentation and health monitoring of bridges.

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It is clear that the development of WIM technology is diverging to solve specific applications to meet defined needs rather than simply being an exercise to prove that the technology is feasible. The technology is going beyond the initial need for better collection of information for pavement design to support of enforcement and tolling, improving safety, and getting information that is more relevant to pavement design, tire pressure and footprints. As the identified needs become less similar, the emphasis in the technology is in improving the accuracy of the estimates that the systems need to produce. Improving and using existing technology is a larger part of the material presented in this technical session than the introduction of new technologies.

The two parts of this session focused on improvements in sensor technology and sensor data analysis for highway WIM systems. The topics addressed include multiple sensor arrays and improving WIM estimates from such systems, identifying vehicles and their weights using bridge WIM through various methods including those with no sensors on the road, a new sensor type and a new WIM system for field weighing of military vehicles.

The work on multi-sensor WIM focused on alternative methods to determine optimal spacing and improve the estimates from the system by using other than simple averaging. The outcomes highlighted were that accuracy was not influenced by profile when determining the location of the array and the fewer sensors present in the array, the simpler the computation methods to produce a reasonable estimate. The former point brought up the question as to whether different trucks characteristics and transverse locations were considered. The response was that due to the use of simulation, and the lack of left and right wheel path profiles in the simulation, location in the wheel path was not thought to be a factor. The presenter further stated that the ideal number and spacing is supposed to be truly road independent because the technique is supposed to take profile into account although a major bump might invalidate that conclusion.

In a sense, the statement about location in the wheel path not having an effect was invalidated by a subsequent paper that discussed the edge effects associated with piezoceramic sensors. This sensor type was investigated in the laboratory and in situ to see if the response was constant across the sensor length. For the type tested it proved not to be but it was demonstrated that the field results could be improved using the information on differences determined in the laboratory. This approach was demonstrated as improving system accuracy but did not change the fact that transverse location of such sensors matters.

As an alternative to the piezoceramic sensors, a new type of in road sensor based on strain gauge technology was presented. This new sensor is believed to have a long term stability of at least 10-15 years. The sensor discussed is intended to acquire tire type, transverse position of vehicles, footprint and pressure and is currently undergoing development and testing.

The other new technology application was a portable WIM system to weight military vehicles in support of aircraft loading. The system using existing technologies has been under development off and on for over a decade. It is faster requiring fewer personnel and producing greater accuracy than current systems. Currently out for procurement, information on cost, configuration and durability could not be provided in response to questions.

Bridge WIM systems have many advantages compared to pavement WIM systems. There is a considerable amount of work continuing in Europe to improve bridge WIM systems. These are non-intrusive for the most part and the majority of current effort is focused on implementing new methods for axle detection so that nothing needs to be put on the road or cut into the pavement. Accuracy of A(5) can be achieved for such systems if the road surface is very smooth. The other advantage to non-intrusive technologies is their usefulness in reducing avoidance associated with enforcement and tolling.

The current issues being looked at with bridge WIM include distinguishing between multiple vehicles on a bridge, clearly identifying distinct axles, and handling multiple span bridges. One presenter indicated that it was possible for a system to produce reasonable results for multi-lane spans of 20 to 30 m with not particularly dense traffic. One approach to axle identification looked at using additional transducers mounted at different longitudinal positions to get velocity that provides highly accurate results but is pavement dependent. Not all bridge WIM systems are focused on weight, one approach discussed focused on getting good classification information even if the GVW estimates were not outstanding. Another proposed approach was a wavelet transformation of the strain signal to give a clear indication of the location of closely spaced axles. This had large computational requirements so that it was not appropriate for real time data interpretation. Most of the questions on bridge WIM systems and analysis were seeking greater clarification on methods and testing conditions. For those studies primarily in laboratory conditions, the answers tended to be that the simplest conditions were being studied to provide proof of concept and for computational efficiency. For field studies, the typical additional research is needed response was most often heard.

SESSION 2 :

RAILWAY WIM

Chairperson: Ales Žnidarič
Co-chair: Victor Dolcemascolo

IMPLEMENTATION OF BRIDGE WEIGH-IN-MOTION FOR RAILWAY TRAFFIC

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Abstract
This paper focuses on implementing existing Weigh-In-Motion technology on railways. Using only simple instrumentation with four concrete embedded sensors, a complete WIM system with axle detection, weighing, track detection and attempted identification of locomotives is implemented for a bridge with multiple railway tracks. The paper presents some very early results and highlights the efficiency of the algorithms and the effectiveness of this type of sensor setup.

Keywords: Bridge, Railway, Train, Weigh-in-Motion, WIM, Influence Line, Calibration, Speed Measurement.

Résumé
Cet article présente la mise en œuvre de technologies du pesage en marche existantes pour les trains. En utilisant une instrumentation simple avec quatre capteurs noyés dans le béton, un système complet de pesage en marche avec détection d'essieu, pesage, détection de voie et tentative d'identification des locomotives est mis en œuvre sur un pont multivoie. Les résultats des premières expériences sont présentés en soulignant l'efficacité des algorithmes et de l'implantation des capteurs.

Mots-clés: Ponts, Chemin de Fer, Train, Pesage en Marche, Ligne d'Influence, Étalonnage, Mesure de Vitesse.

橋樑動態地磅於鐵路之應用

摘要：
本文主要針對既有之動態地磅 (Weigh-in-Motion, WIM) 技術於鐵路上之應用進行討論。本研究於一多軌道的鐵路橋梁上安裝完整的動態地磅系統，此系統僅以四個埋入混凝土中的感測器及簡單儀器組成，但其已擁有車軸、車重、軌道等偵測功能，並且期望以上述設備判別列車之形式。本文提出一些早期的試驗結果，並著重說明此種演算法之效率以及感測器設置之效果。

關鍵字：橋樑、鐵路、列車、動態地磅、WIM、影響線、校估、車速量測

1. Introduction

Until recently, most of the research in the area of bridge design has concentrated on the study of the strength of materials and relatively few studies have been performed on assessing actual traffic loads and their effects on bridges. As a result, the correctness of the traffic loads, current safety factors and dynamic amplification factors used today by bridge engineers for design and assessment of bridges can be questioned (James, 2003).

Within the bridge engineering community, there is today a considerable interest in the problem of measuring actual traffic loads and their dynamic effects on bridges. In Sweden, several bridges have recently been instrumented by the authors, where strain transducers were placed on the soffit or embedded in the bridge deck. This relatively inexpensive instrumentation makes it possible to:

- Determine vehicle characteristics such as speed, axle distances, and static axle loads. This is usually referred to as Bridge Weigh-In-Motion (B-WIM) system, as such an installation converts the bridge into a scale that weighs traffic while moving over the bridge (Quilligan et al., 2002; Quilligan, 2003).
- Measure the true dynamic response. The dynamic amplification factors can then be determined using simulations based on measured speeds, static axle loads and distances.

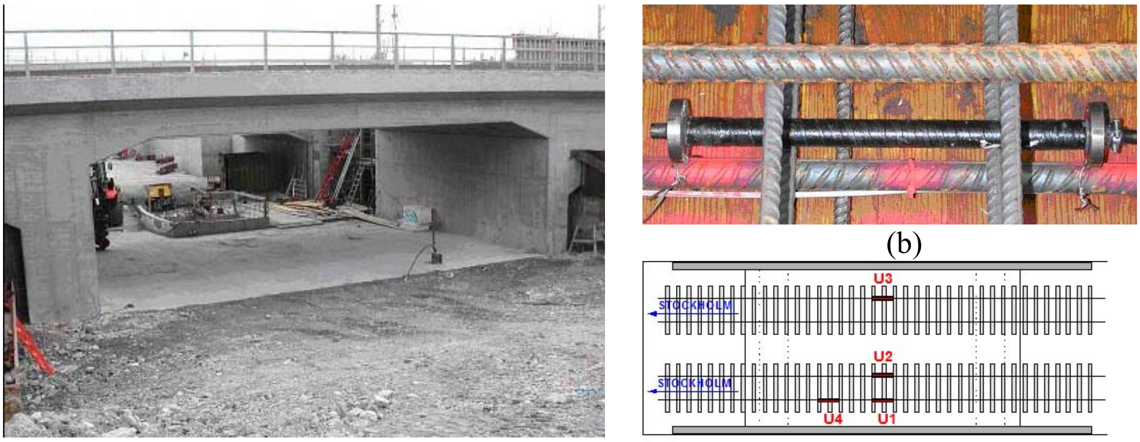
This paper describes the instrumentation of a newly constructed integral type railway bridge in Stockholm. The fundamental aim of this study is to increase the knowledge of actual traffic loads and their effects on railway bridges through measurements and numerical simulations. For a more detailed description of the instrumentation objectives, etc. (Karoumi, 2004).

2. Description of the Bridge

At the new Årstaberg railway station, three railway bridges have been built during the year 2003. The bridge carrying two ballasted railway tracks for traffic heading towards the city of Stockholm was instrumented and opened for traffic in July 2003 (Figure 1(a)).

The bridge has a span of 14.4 m, is made of reinforced self compacting concrete and is of the integral type, i.e. the construction is continuous as it is constructed without movement joints at the junction of the deck with abutments. The deck supporting the tracks is 0.8 m to 1.3 m thick and the sidewalls are 0.9 m thick. The sidewalls are also continuously connected to a 1.0 m thick bottom slab.

For the verification of the measurements and as a basis for analysis and numerical simulations, FE-models of the bridge have been developed. Some simulations of the dynamic response of the passing train are made using a program developed by the second author and described in (Karoumi, 1998). The results of these simulations are not presented here due to space limitation however they can be found in Karoumi 2004 and future reports.



(a) (c)

Figure 1 - (a) the Instrumented Integral Bridge during Construction; (b) Resistance Strain Transducer Produced at KTH; (c) Location of the Embedded Sensors U1-U4

3. Description of the Instrumentation and Data Acquisition System

Four special resistance strain transducers (Figure 1(b)), produced at The Royal Institute of Technology (KTH) in Stockholm, were embedded in the concrete section of the deck supporting the two railway tracks. The total length of each transducer is 300 mm. Between the two anchor plates, 50 mm in diameter, there is a strain element made of a steel tube, 10 mm in diameter, to which four strain gauges are attached. The strain gauges were connected as a full Wheatstone bridge. The cables are routed inside the steel tube, which was later encapsulated with several coatings for protection and to ensure that the deformations are only introduced to the anchor plates. The data acquisition system MGCplus from Hottinger Baldwin Messtechnik (HBM) was chosen for this instrumentation, connecting each strain transducer to a ML55B amplifier.

As the main interest is to measure/calculate actual traffic loads and load effects on the high speed line, three of the transducers were placed under that track (Figure 1(c)). Only one transducer, U3, was placed under the second track which is for commuter trains that are of less interest in this project. Since multiple sensors are located at the centre of the bridge, but beneath the different tracks, it can be easily determined in which of the two lanes a train is running. In the case of multiple trains passing the bridge simultaneously, a low resolution splitting of the signal into one signal for each track can also be accomplished.

4. B-WIM algorithm

B-WIM or bridge weigh-in-motion is the process of converting an instrumented bridge into a scale for weighing passing vehicles. This section describes the implemented railway B-WIM algorithm which is partly based on previous research by Quilligan (2003).

The B-WIM algorithm, which has been implemented in the MATLAB language, produces the following results:

- The position of each axle.

    - The load of each axle.
- The speed and acceleration of the train.
- The direction of the train.
- The track on which the train is crossing.

Of course, as the resolution of the B-WIM algorithm depends on the bridge type and if the track is ballasted or not, for most bridges, including the Årstaberg bridge, the individual axles of a bogie can not be detected. Consequently, for such bridges the B-WIM algorithm works with bogies instead of axles.

The algorithm works using the attributes described in the previous paragraph to calculate a simulated strain curve. The square difference between this curve and the actual measured strain curve is then minimized. The algorithm consists of the following steps:

1. Load the calibration data, including the influence line for each sensor.
2. Calculate the speed of the train using the phase difference method described in section 4.1.
3. Make an initial guess of the axle positions and load.
4. Adjust the axle positions, axle load and the speed and acceleration of the train to minimize the difference between the calculated strain curve and the actual strain curve.

4.1 Determining the speed of the train using the phase difference between signals

The B-WIM algorithm described in the previous section relies on a good initial guess of the train speed. Because this calculation needs to be performed before the actual B-WIM calculation, it must not depend on knowing anything about axle positions etc. One way of doing this is to identify a peak on the strain curve on both sensor U1 and sensor U4 (see Figure 1(c)), and measure the time difference between the two peaks. This time is the time it takes for the train to travel the distance between the two sensors, from which the speed can be easily calculated. Determining the speed of a train using the method described above relies on identifying a peak which represents the same axle on both sensor U1 and sensor U4. Though this method provides a reasonable first guess it is difficult to accurately computerize the operation of identifying peaks, since noise may shift the maximum strain measured away from the actual peak. A simpler and more accurate method consists of finding the phase difference between the signal for the two sensors which minimize the difference between the two signals. This can be expressed mathematically as trying to find the value p which maximizes the following equation:

$$\sum_{n=1}^{N-p} s_{1,n} s_{4,n+p} \Big/ (N-p) \qquad (1)$$

where $s_{a,b}$ is the strain recorded by sensor a at time step b and N is the number of samples.

Figure 2 shows the result of calculating the above equation for varying p. The highest peak is clearly identifiable, and the p for which it occurs is inversely proportional to the train speed. This method is fast, robust and accurate; furthermore, it does not require any knowledge about the train passing by. The only additional information beside the strain curves which needs to be supplied is a constant which should theoretically be the distance between the sensors U1 and U4.

In practice the influence line for sensors which are not placed at the centre of the bridge will be asymmetrical, which results in a systematic error. Because of this, there is a need for a calibration run using a train travelling at a known speed.

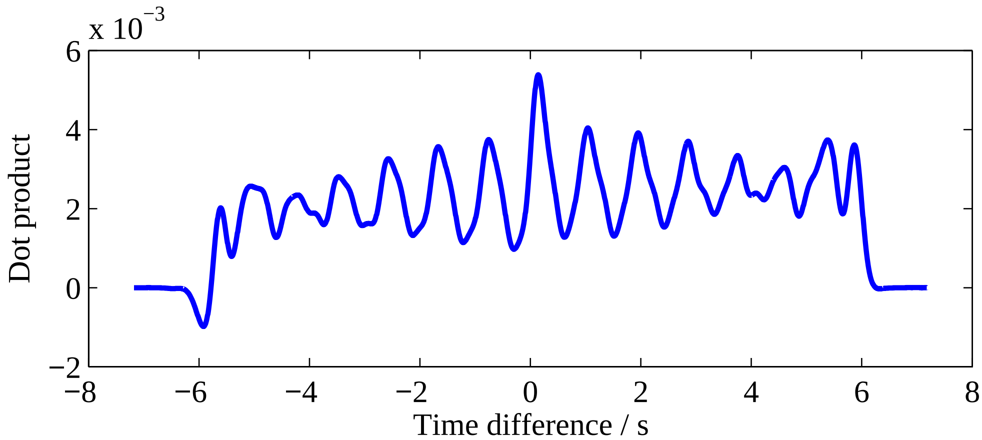


Figure 2 – Variation of the Difference between the Signals when a Phase Difference Is Introduced

4.2 An Initial Guess

The first step of the actual axle detection consists of making an initial guess of the train properties. The train data consist of information on the number, position and weight of each axle, and the speed and acceleration of the train. The initial guess on train speed is calculated using the phase difference as described above. Given an axle position, a reasonable estimate of the axle load can be obtained by using the measured strain at the time of the axles crossing over the sensor. This leaves us with the problem of detecting the number of axles and their positions. This is done heuristically by looping over the following steps:

1. Calculate an error curve by subtracting the simulated strain curve from the actual measured strain curve.
2. Locate the highest peak of the error curve.
3. If the peak is lower than one third of the highest peak in the actual strain curve, the calculation is finished and the axle identification process is stopped.
4. If the peak is closer than one meter to another axle, the calculation is finished and the axle identification process is stopped.
5. Otherwise, place a new axle at the peak.
6. Adjust the axle positions, load and speed of the train to minimize the error curve.

4.3 Adjusting the Train Data

After an initial guess of the train properties has been made, the guess is adjusted to minimize the difference between the actual measured load curve and the one generated using the train properties. This is a non-linear optimization problem which can be defined as minimizing

$$O(y) = \sum \left(L_c(y) - L_m \right)^2 \qquad (2)$$

to find $y = \{v, a, p_1, p_2, ...p_N, m_1, m_2, ...m_N\}$ where $O(y)$ is the objective function, v and a are the speed and acceleration of the train, p_n and m_n are the position and load of the n:th axle, $L_c(y)$ is a function that generates a load curve given a set of train properties as described in section 4.4, and L_m is the actual load curve.

Originally, the MATLAB function fminsearch was used to perform the minimization. But since this was found to perform slowly and inaccurately if the initial guess was not extremely accurate, an intermediary step was used. The chosen approach was to find the local minimum along one degree of freedom at a time. The minimization of axle load, speed and acceleration use discreet steps of one percent when adjusting the values, whereas the axles are adjusted one time step at a time. After the train data has been adjusted using the above described minimization function, a call to fminsearch is used to increase the precision. Figure 3 shows how close the results of the axle detection algorithm match the actual measurements.

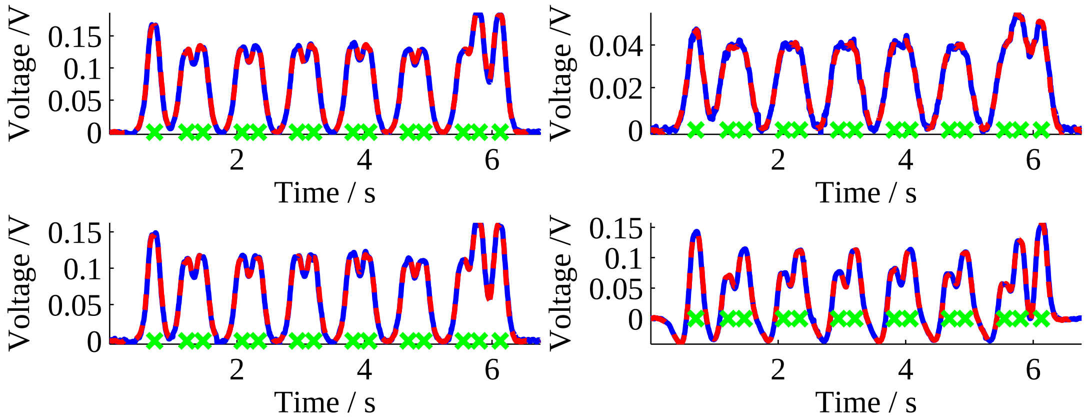


Figure 3 - The Measured and Simulated Strain for a Train with One Locomotive and One Power Wagon (The first column contains plots for sensors U1 and U2, the second row contains plots for U3 and U4, the solid blue line is the measured strain, the dashed red line is the calculated strain and the green crosses are detected axle positions)

There are already several more suitable optimization algorithms available which would most probably further minimize the error. Since it has been found that the main error source is not inaccurate minimization but dynamic effects, no other minimization algorithms have been tested.

4.4 Generating the Simulated Load Curve

The simulated load curve is calculated using the influence line of the bridge at each sensor and the load and position of each axle of the train as well as the speed and acceleration of the train. The contribution of a given axle to the strain at a given sensor is calculated using Moses algorithm (Moses, 1979). The total strain curve for a sensor is simply the sum of the strain of each axle.

4.5 Calibrating the System

System calibration is performed automatically, i.e., using locomotives from random crossing traffic without requiring user interference, and consists of the following steps:

1. Make an initial guess on the appearance of the influence line. Several guesses can be made using different functions to generate the influence line.
2. Perform a regular axle detection using the guessed influence line.
3. Find the influence line that minimizes the least squares difference between the actual strain curve and the strain curve generated using the train data.
4. Calculate the proportionality constant between axle load and strain sensor voltage. For this step, it is obviously necessary to know the axle loads of the locomotive.

The algorithm will fail if none of the influence lines chosen in the first step match the actual influence line. This has not been found to be a problem on the Årstaberg bridge. Figure 4 shows the strain curve and the error curve during calibration using a Gauss bell influence line. The last step of the calibration deserves some elaboration. Quilligan (2003) uses Moses equation to generate an influence line. To improve clarity and program performance we have chosen to modify this algorithm to make the least squares approximation explicit.

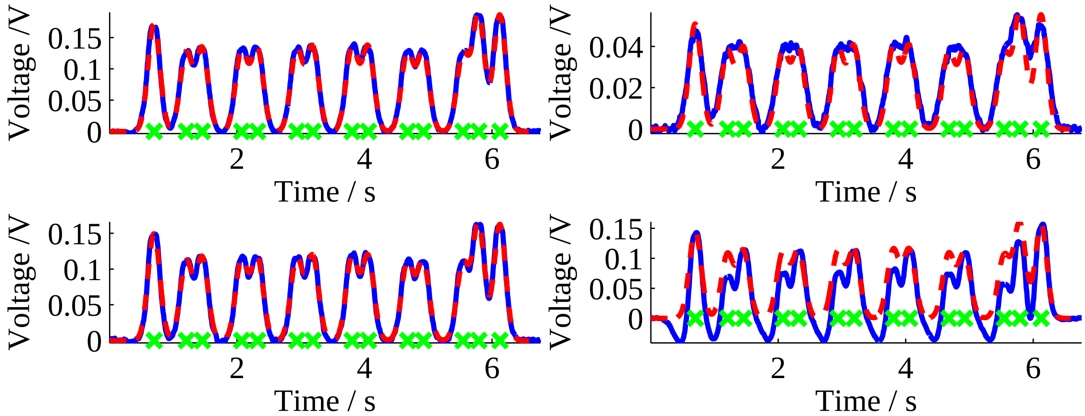


Figure 4 - The Measured and Generated Load Curve Using a Gaussian Bell as Influence Line (The first column contains plots for sensors U1 and U2, the second row contains plots for U3 and U4, the solid blue line is the measured strain, the dashed red line is the calculated strain and the green crosses are detected axle positions)

The goal of the last step is to calculate the influence line $\bar{i}$ of a bridge given a measured strain curve and the system properties of the train. This is done by constructing a matrix $\mathbf{A}$, which is of size $T \times L$, where T is the number of strain curve samples and L is the number of elements in the desired influence line. The element on the n:th row and the m:th column of $\mathbf{A}$ corresponds to the strain at time step n generated by any axle at point m on the influence line. This means that $\mathbf{A}$ will be a sparse matrix consisting of one diagonal line for each axle of the train. If $\mathbf{A}$ is multiplied by a vector representing an influence line $\bar{i}$, this will result in a strain curve. Since we want this strain curve to approximate the measured strain curve, which we will call $\bar{r}$, we want to find an influence line $\bar{i}$, which will satisfy the relationship $\mathbf{A}\bar{i} = \bar{r}$. Since we can determine the number of samples in our generated influence line, it might seem like a good idea to use L=T.

This is not the case, since it will usually result in a singular $\mathbf{A}$. Instead one should choose $L << T$ and use the least squares minimization of the above system. This will result in an accurate estimate of $\bar{i}$.

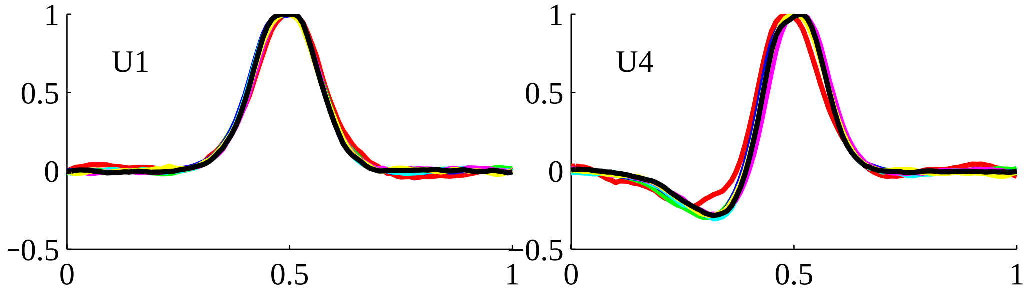


Figure 5 - The Influence Lines for Sensors U1 and U4 Generated by Calibration Using Seven Different Trains

The influence lines generated using the above algorithm have a very high accuracy. Figure 5 shows the influence line generated by seven different sets of trains passing over the Årstaberg Bridge. A slight displacement between the influence lines can be seen, but this does not affect the accuracy of the calculations.

4.6 Determining the speed of the train using a single strain curve

This is an alternative method to the one described in section 4.1. It is slightly more accurate, however because it requires knowledge about the number of axles and axle positions of the train, it can not be used in the initialization phase of the calculations.

When constructing a simulated strain curve, the influence line is scaled in the time domain in order to best match the actual strain curve. The width of the influence line in the time domain is actually the time it takes for an axle to pass the bridge. If we know the length of the bridge, we can simply divide the two to calculate the speed of the train. This idea runs in to a similar problem to the one encountered when using the phase difference to calculate the speed. Since the influence line used in the algorithm is based on measurements and not accompanied by the exact time an axel enters/leaves the bridge, the actual width of the influence line is not known. Because of this, it is in fact not a "real" influence line; the x-axis is normalized and it's units unknown. To solve this problem, one simply has to calculate the length of the calculated influence line during the calibration. This length does not have to be the bridge length. In fact, the bridge length does not need to be known for this approach to work.

5. Test Details

A set of measurements using the four strain sensors, as well as an accelerometer and a laser speed measuring pistol of the same type used by the police, was done for 33 train sets. The speeds of the recorded passing trains (commuter trains, high-speed trains, and regional trains) varied between 38 to 114 km/h. Since there are several different methods to calculate the train speed from the collected sensor signals and it is desirable to know the accuracy of each method, the laser speed pistol was also used to get accurate measurements of the train speeds. The accelerometer data has not been used here, but will be used and presented in future work.

6. B-WIM Results

There are, as described above, several means of calculating the speed of the train from the collected data. Figure 6 shows how the trains speed, calculated using the two different algorithms described in sections 4.1 and 4.6, varies with its speed as measured by the speed laser pistol (considered to be the real speed). The standard deviation of the error in speed calculations are about 5% for both calculation methods. It should be noted that the speed calculations are co-variant which implies that a significant portion of the error comes from the laser pistol. Such errors originate from various sources, including train acceleration (speed measurements where done about 100 meters before the bridge), the pistol not being completely parallel to the train tracks at the time of measuring and other sources of error in the speed pistol.

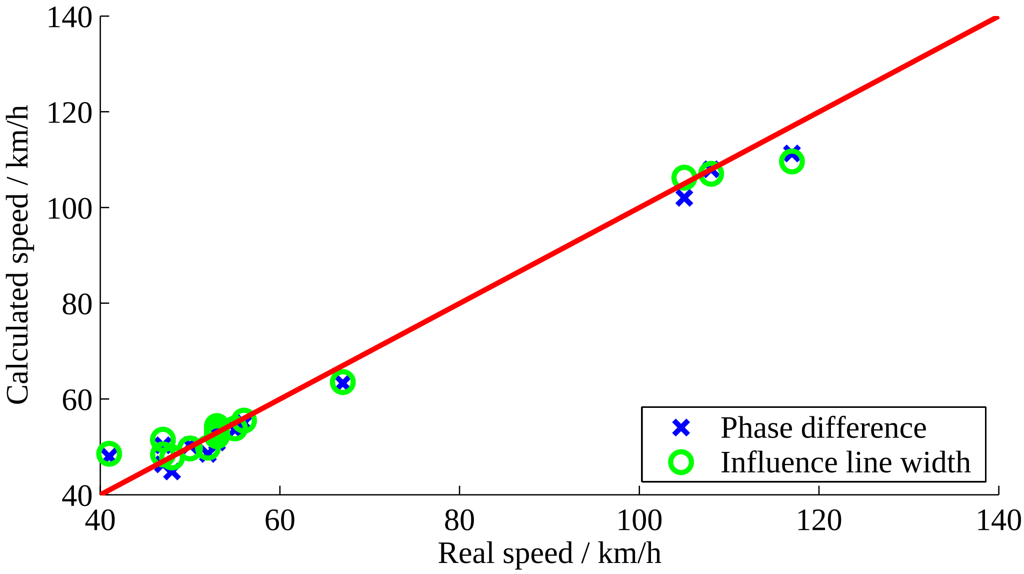


Figure 6 - The Measured "Real" Speed of Thirteen Commuter Train Sets and Five Regular Train Sets Along the x-Axis and the B-WIM Calculated Speed on the y-Axis (Two different methods for calculating the speed were used, these are shown separately)

Figure 7 shows how the locomotives calculated gross weight varies with its real gross weight. The standard deviation of the error in estimated gross weight is approximately 2%. The error in estimated bogie load is approximately 2.5%.

Figure 7 also shows how the error in the locomotives calculated gross weight varies with the speed of the locomotive. There is no obvious tendency towards speed dependency. It should be noted that the variations in speed is small, such tendencies might well be noticeable at higher or lower speeds. The speed values used to produce Figure 7 is the calculated speed, not the speed as measured by the laser pistol. This is because the laser pistol was not used on all of the trains used to produce the figure. It should also be noted that several of the trains used to produce Figure 7 had more than one locomotive. It is interesting to note that there appears to be a slight co-variation in the error of multiple locomotives in the same train.

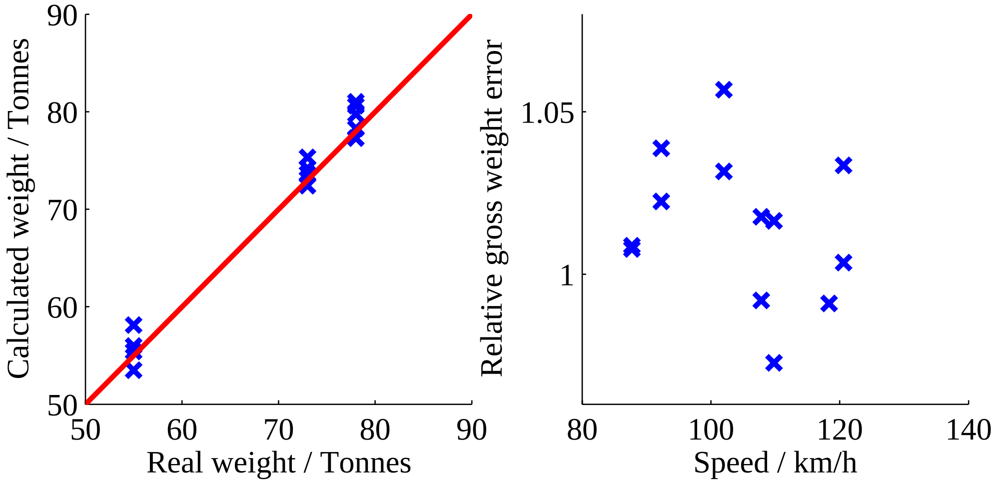


Figure 7 - The Variation of Calculated Gross Weight Estimate with Real Gross Weight and the Variation of Gross Weight Estimate Error with Speed for 13 Locomotives

7. Conclusions

This paper describes the ongoing development and testing of a B-WIM system for railways. The results are encouraging and further research is planned.

While the phase differences of the signals give an excellent starting guess for the speed of the train, it was found that measuring the width of the influence line gives slightly more accurate final results. The standard deviation of the error in the two calculation methods is about 5%. It is noteworthy that the speed calculations performed very well for trains on the commuter track, even though this track only had one sensor underneath it. The information from the sensors placed under the neighboring high speed track provided enough information to accurately complete the phase calculations described in section 4.1.

The accuracy of the weight calculations is high, the standard deviation in locomotive gross weight error is about 2% and the standard deviation of the error in bogie weight is about 2.5%. For the Swedish railways, this is not always enough to safely use as the sole means of identifying the type of locomotive of the train. To do this, the axle distances of the locomotive should also be taken into account.

Future work will focus on classifying the system according to the WIM specifications, evaluating dynamic effects, implementing the system in a real-time environment as well as studying accelerating trains in order to make the axle detection algorithm more robust.

Acknowledgement
The funding for this project is provided by the Swedish National Railway Administration (Banverket) and is gratefully acknowledged. The authors of this paper would also like to thank the laboratory technicians Stefan Trillkott and Claes Kullberg who went above and beyond the call of duty for this project.

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GOTCHA: COMPACT SYSTEM FOR MEASURING TRAIN WEIGHT AND WHEEL DEFECTS

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Abstract
A compact measuring system has been developed on behalf of ProRail (former Railinfrabeheer), the Dutch Infrastructure manager) and NedTrain to determine the weight of trains and to identify wheel defects under operational train speed. Gotcha stands for 'Guard On wheel Tread Condition on tHe TrAck'. The GOTCHA system is developed by NedTrain Consulting in cooperation with Baas R&D. With a way side measurement system using glass fibre sensors, the deflection of the rail is measured during the passage of a train. With an advanced post processing method, the wheel defects and the static and dynamic loads on the infrastructure are determined from the sensor signal. This system is currently in full operation in the Netherlands and it is a fully integrated part of the wheel maintenance process of NedTrain.

Keywords: WIM, Weigh-in-Motion, Wheel Defects, Wheel Flat, Train Weight, Axle Load.

Résumé
Un système de mesure compact a été mis au point pour ProRail (ancien Railinfrabeheer; l'exploitant néerlandais de l'infrastructure) et NedTrain, pour déterminer le poids des trains et pour identifier des imperfections des roues à la vitesse de service. GOTCHA veut dire *Guard On wheel Tread Condition on tHe trAck* [= surveillance de la condition de la chape des roues sur le rail]. Le système GOTCHA a été mis au point par NedTrain Consulting en collaboration avec Baas R&D. La déflexion du rail est mesurée pendant le passage du train avec un système de mesure au bord de la voie; ce système est équipé de détecteurs en fibre de verre. Les imperfections des roues ainsi que les charges statiques et dynamiques sur l'infrastructure sont identifiés du signal du détecteur, avec une méthode avancée après traitement.

Mots-clés: Imperfection des Roues, Méplat, Poids des Trains.

GOTCHA：列車重量與車輪瑕疵量測整合系統

摘要：
ProRail（前 Railinfrabeheer，即荷蘭基礎建設管理單位）及 NedTrain 聯合開發之了一套整合量測系統，可用以量測列車運行速度下之列車重量並進行車輪瑕疵之判別。GOTCHA 全名爲 Guard On wheel Tread Condition on tHe trAck， 該系統由 NedTrain 顧問公司與 Bass R&D 合作開發。當列車通過時，側貼於軌條之玻璃纖維感測器量測系統可量測鋼軌的撓曲值。感測器的訊號可透過先進的後處理法以決定車輪瑕疵以及靜、動態載重。本系統正全面在荷蘭運作中，其並爲 NedTrain 車輪養護流程中的一部份。

關鍵字：WIM、動態地磅、車輪缺陷、列車重量、軸重

1. Introduction

When determining costs for the use of the railway network, ProRail considers the number of train kilometres and the weight of the train as the most important parameters. Also, in the future a bonus/penalty system based on the wheel quality of passing trains will be implemented. It is therefore important that regardless of the operating conditions the weight is determined with a maximum reliability.

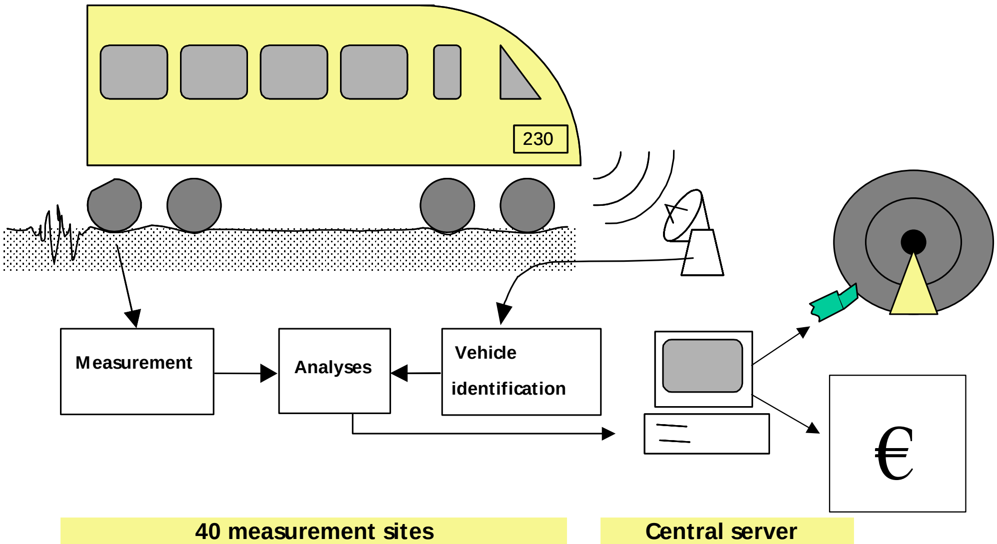


Figure 1 - GOTCHA System

Amongst other things, NedTrain carries out the maintenance of the vehicles owned by the Dutch Railways (NS) and uses the information concerning the wheel tread quality to control the maintenance work. Out of roundness measurements in the maintenance shops are therefore cancelled. To achieve this, the accuracy of the GOTCHA system had to be at least equivalent to the former rejection criteria. It must also be possible to make a distinction between different types of defect, such as eccentricity, squaring, flats, etc. This is important for improving maintenance strategies and creates the possibility to match rejection criteria to the type of defect.

1.1 Description of the system

In total 40 measuring systems are in operation in the Netherlands. All of them are used to collect train weight and 20 are used for train weight as well as wheel quality, resulting in 95 percent of all axles being measured at least one time in every three days. One GOTCHA system consists of four glass fibre sensors mounted in the track (two on each side) and one antenna for vehicle identification (see Figure 1). The measuring signal is analyzed on site and linked to the vehicle number. The results (defect values and weight per axle) are passed on from each measuring site to a central server. Here a choice is made based on the severity of the defect and an order is generated in the maintenance system. Furthermore, each maintenance shop will have the capability to check the GOTCHA database to find out whether the vehicle in question has any wheel defect.

1.2 Sensorsystem in the Track

With the GOTCHA system the wheel signatures are measured with a specially developed sensor using modern glass fibre sensor technology. The sensor is mounted underneath the rail and connected to a system box with display unit along the track (see Figure 2). This unit generates an optical signal, which is fed to the sensor via an optical glass fibre cable. The sensor converts the (extremely slight) vertical deflection of the rail due to the passing wheel into a change in the optical signal. This signal is converted by the display unit to a precise electrical signal which is then available for further processing.

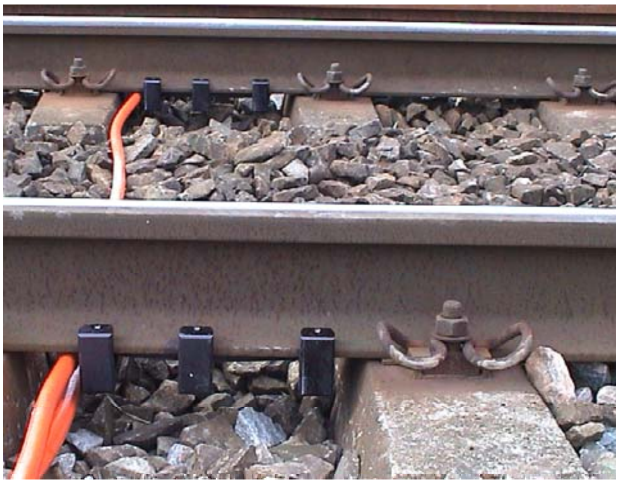


Figure 2 - Two Sensors in the Track (4 in Total)

The glass fibre sensor is placed in a robust metal housing which is fastened to the rail with snap-on clips which are locked with bolts. The display unit uses the optical signal to check whether the sensor has been connected correctly. Proper installation and functioning of the sensor is continuously monitored while the GOTCHA system is in operation. Up to 1 kHz the sensor's frequency response is practically flat and therefore the signals can be interpreted precisely. Because of the use of optical technology there is no electrical connection with the rail and the system is not sensitive to any electromagnetic influence. The resulting signal-to-noise ratio is therefore very high and enables a very precise recording of the wheel quality and axle weight.

The modern, mechanical design of the sensor does not require any specific maintenance and is quick and easy to install, without having to decommission the track. The principle of the sensor is shown in Figure 3.

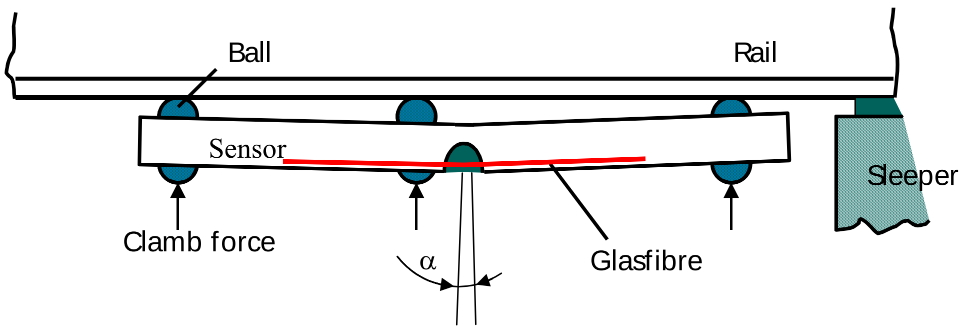
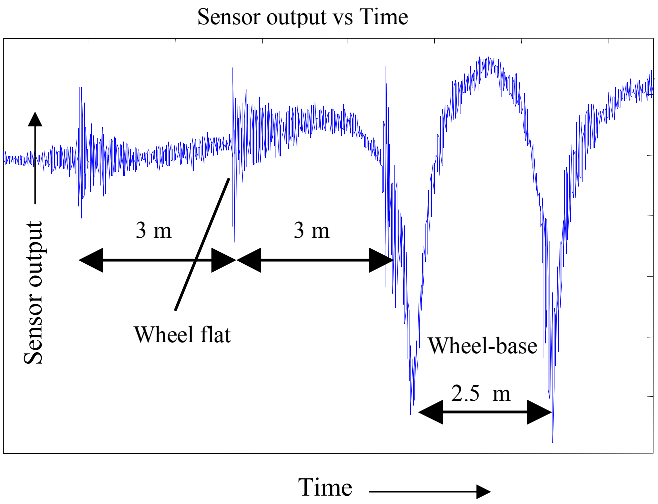


Figure 3 - Principle of the Sensor under the Rail. The Angle, α, Is the Measured Quantity and Follows the Vertical Bending of the Rail.

2. Wheel Defects

Figure 4 shows an example of the sensor signal for the passage of a bogie with a wheel flat on one wheel. The vehicle speed was 38 m/s and the frequency range of the signal 10-1500 Hz. It can be seen that the sensor detects the wheel flat for three consecutive wheel revolutions.



2.2 Characteristics of the sensor system

The sensor is mounted underneath the rail by means of a three point support. The absorbed light in the sensor is proportional to the deflection angle of the sensor. The glass fibre sensor is mounted on the housing with an initial deflection angle resulting in a region of linear response around this working point. The bending of the sensor is a result of a vertical external force on the rail and besides the amplitude of the force, it depends on both the frequency and the distance between the sensor and the impact location.

2.2 Frequency dependency

Because the super structure is part of the measurement system it acts as a dynamic system itself. The dynamic behavior can be visualized by means of a transfer function relating the vertical wheel-rail force to the bending of the sensor. This function is shown in Figure 5 for a relative distance between sensor and wheel-rail force of 1 m and a vehicle speed of 30 m/s. Up to 70 Hz the response is flat, meaning that the sensor actually measures the wheel- rail force. From 70 – 200 Hz (in this range out of roundness can be expected) the response is highly depending on the frequency; the sensor system is sensitive to frequency changes within this range. Therefore the

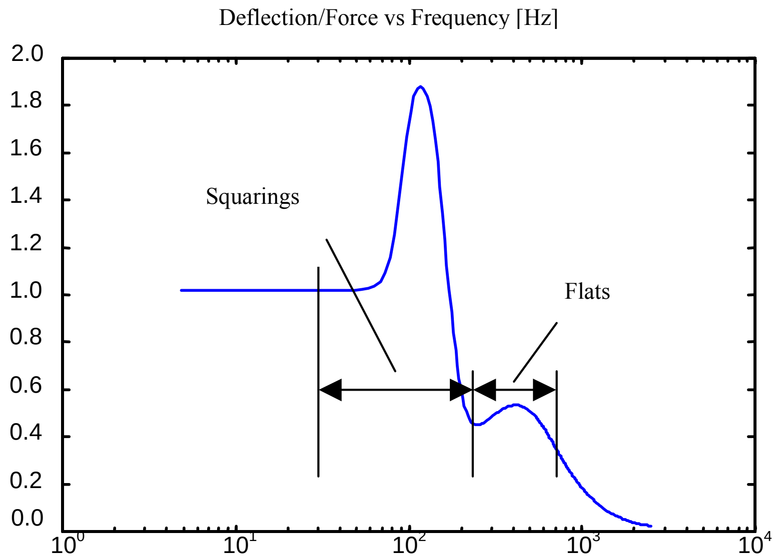


Figure 5 - Transferfunction of the Sensor System

sensor signal shall be corrected here to achieve a good correspondence with the actual wheel–rail force. Within the 200-800 Hz range (wheel flats) the transfer function is relative flat again and no correction to the signal is needed.

The relative distance between the sensor and the location where the defect hits the rail influences the sensor signal; the vibration of the rail will partly damp out before it will reach the sensor. Figure 6 shows a typical representation of this phenomenon. It can easily be seen that the amplitude decreases with increasing distance between sensor and impact location. This effect is also frequency dependent. Furthermore the influence of stiffness variation as a result of the discrete support by the sleepers is present. A local minimum of the graph indicates the existence of a node in the deflection of the sensor system; wheel defects hitting the rail on this position will be less visible for the sensor.

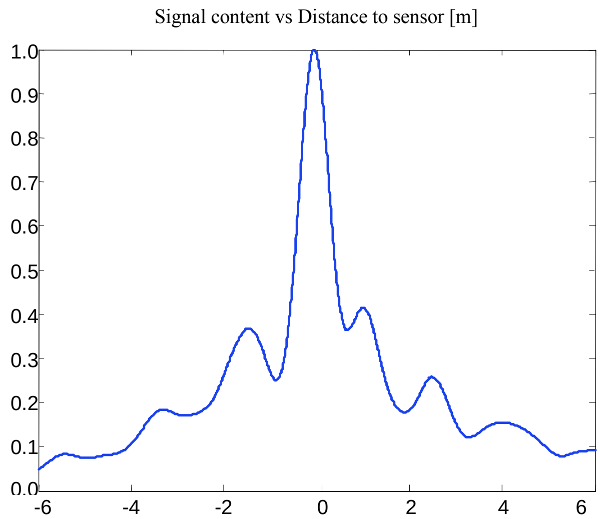


Figure 6 - Location Dependency

The post processing of the measurement signal is corrected in such a way that the diagnosis of the wheel is consistent within the range as shown in Figure 6. Special attention is given to the distinction between the diagnoses of two adjacent wheels. The correction shall not lead to a wheel being wrongly rejected because of vibrations coming from an adjacent wheel.

2.3 Development of the analysis method

The device used to measure the bending of the rail is compact and easy to install, but requires advanced signal processing in order to be able to determine wheel quality and axle load with sufficient reliability. NedTrain Consulting developed the software required to process the signals using MATLAB (1984-2000). During the software development phase two test sites were set up to provide the necessary measuring signals. To support the development of the analysis method, a measuring site model was created in the multi-body package ADAMS (Version 12). Using this model measurements were carried out in the same way as in reality. As an input the actual wheel geometry was used as measured in the maintenance shop. The results of the calculations were verified with the measured response of the same wheel (see Figure 7). The model is used to perform experiments and parameter changes, which would be expensive and difficult to carry out in practice. e.g. changes to wheel spacing and the position at which a defect hits the rail relative to the sensor. The result of these experiments is a location-dependent routing function, which converts the measuring signal into the dynamic force along one wheel revolution. The correction for the dynamic properties of the sensor system is implemented by means of a 6th order discrete filter function covering frequencies up to 1000 Hz.

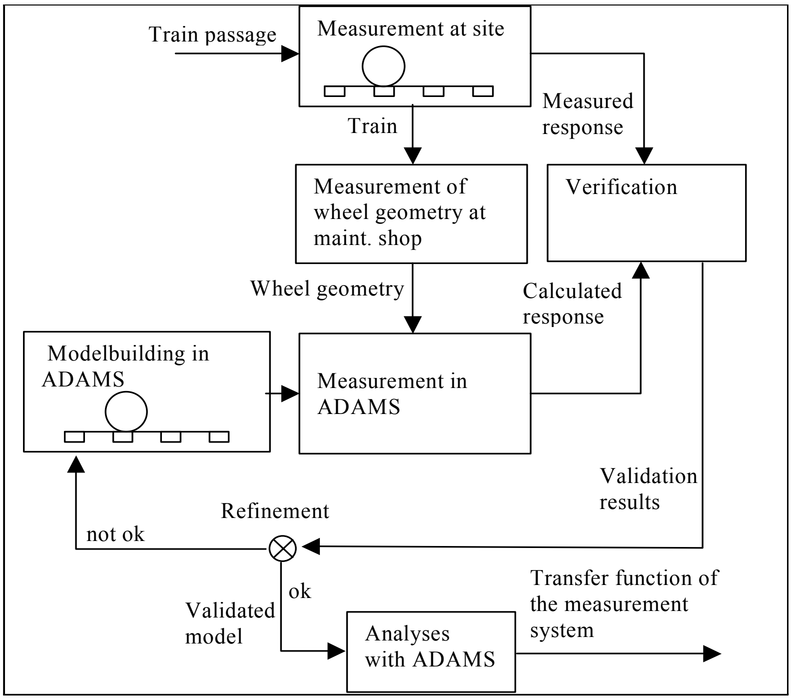


Figure 7 - Development of the Analyses Method

2.4 Assessment method for wheel defects

The state of the wheel is described by means of the ‘defect value’. The defect value is described as the effective value for the dynamic force between wheel and rail for one complete wheel revolution. This way the type of defect as well as the number of defects along the wheel circumference is taken into account. Figure 8 shows the wheel-rail force for one wheel revolution.

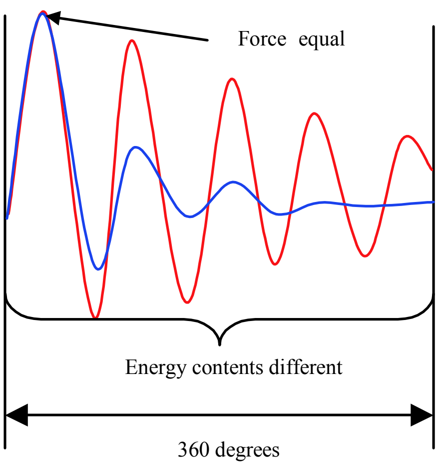


Figure 8 - Rejection Criterion by Means of Defect value

When taking only the maximum force into account both signals will be evaluated equally. However the energy content of the red signal is much higher compared to the blue line and will be less tolerable.

Also a method is implemented to correct for small track irregularities that might be present at or near the measurement site.

2.5 Results

Some results of the measuring system are presented for the wheel defect functionality as well as the train weight part. An important factor for a measuring system is the reproducibility of the diagnosis. Figure 9 gives an example of the results for a passenger train, which has passed the same measurement site three times. This figure also shows the wheel contour measurement of the two wheels with the maximum defect value.

The type of defect and the number of wheel defects are also considered. Up till now a limiting value for the out of roundness of 0.5 mm is used in the maintenance shops in the Netherlands. During 2002 this geometric criterion has been replaced by the defect value.

It can be seen that the deviation between the measurements is minimal. The distinctive capacity is more than sufficient to be able to control wheel maintenance. The rejection criteria depend on the type of rolling stock. In general the first level is about 10 kN, where the concerning axle is allowed to be in service up till next maintenance. Above 20 kN the rolling stock will be taken out within 5000 km. In general the maximum force is about 3 times the RMS value.

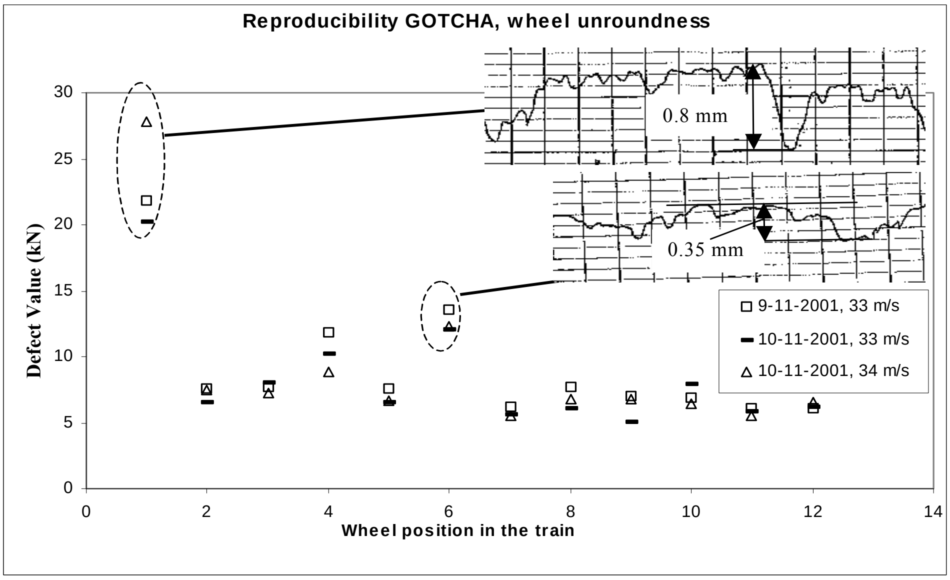


Figure 9 - Measurements of a Train (ICM 4074, Left Side). The Measured Wheel Contour is Shown Top Right.

3. Train Weight and Axle Load

The train weight is the sum of the individual wheel loads. The wheel load is determined from the amplitude of the measured signal. The measured signal is closely related to the vertical bending in the rail. For understanding, the superstructure (track including the rail) is simplified by an elastic beam with a bending stiffness, EI, (the rail) which is continuously supported by an elastic foundation with founding coefficient, k (Esveld, 2001). A vertical force, Q loads the rail (see Figure 10).

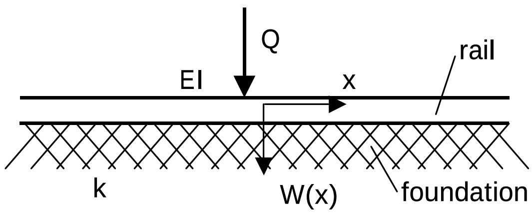


Figure 10 - Beam on elastic support

From this model, the following relationships can be derived: For the vertical deflection, w,

$$w(x) = \frac{Q \cdot L^3}{8 \cdot EI} \cdot \eta(x) = \frac{Q}{2 \cdot k \cdot L} \cdot \eta(x) \tag{1}$$

where L is the so called characteristic length, determined by:

$$L = \sqrt[4]{\frac{4 \cdot EI}{k}} \qquad [m] \tag{2}$$

and η is the shape function:

$$\eta(x) = e^{-x/L}[\cos\frac{x}{L} + \sin\frac{x}{L}] \qquad x \geq 0 \tag{3}$$

The maximal vertical deflection of the rail:

$$w = \frac{Q}{2\sqrt{2}EI^{1/4}k^{3/4}} \tag{4}$$

The maximal curvature of the rail:

$$\frac{d^2w}{dx^2} = \frac{Q}{4EI^{3/4}k^{1/4}} \tag{5}$$

3.1 Sensitivity to Track Construction Parameters

The bending of the rail is far more independent from the track parameters than vertical deflection. This follows from Equations 4 and 5. The maximal bending is mainly dominated by the bending stiffness of the rail which is the only well known and constant parameter in time. Even for different types of rail, differences are limited. The foundation constant, k, can vary significantly over different superstructures and even in time. But even an extreme factor like 16 would only double the maximal bending.

3.2 Automatic Calibration

Especially for railway WIM systems, the calibration can be automated easily or at least it can be monitored automatically. The calibration is automated using in the following train types given in decreasing preference:

- Electric locomotives
- Diesel locomotives
- Electric multiple unit passenger trains
- Diesel multiple unit passenger trains

In this list the variation of the weight increases. Though the variation can be up to 20 percent, it follows a certain pattern along the week that can be recognized by special algorithms. After some time, typical a week, the software is able to find the periods where passenger coaches are nearly empty. Consequently calibrating on the same moments prevents the calibration from getting an uncontrolled offset, though any correlation of the calibration with the day cycle, like temperature would result in a bias. Fortunately, no serious influences are found for tracks with a reasonable quality. This method typically leads to one percent underestimation when the 'nearly empty' trains would have a coefficient of occupation of 10 percent (example of mat '64, Dutch rolling stock used for calibration if no locomotives passes by). This rather good result is due to the low ratio of tare to the empty mass of passenger trains.

3.3 Recognition of Bad Track Properties and Inaccuracy of the Estimated Train Weight

The quality of the measurement depends on the condition of the track and wheel. Due to track irregularities dynamic forces can occur resulting in a deviation of the estimated axle weight.

Train weight is used as a factor in calculating the track access charges. For this reason the performance of the WIM systems are monitored permanently, combined with the automatic calibration. The monitoring is based on the following aspects:

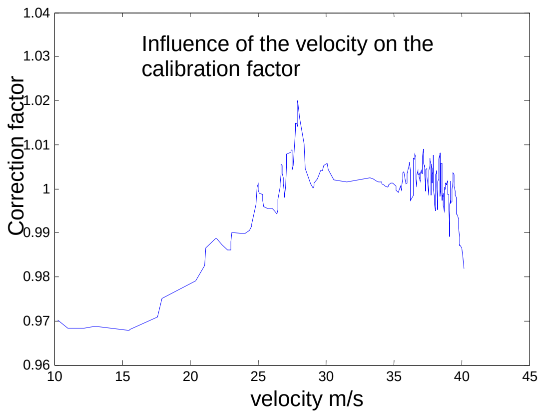


Figure 11 - Influence of the Velocity on the Calibration

- Stability in time. Although track parameters can differ in time, the calibration stays very stable.
- Deviation over the speed range of the site.
  This is a powerful indicator. The form of the graph indicates the type of irregularity such as short wave rail defects and long wave misalignments, which can be coupled to the type of maintenance (Figure 11). Small peeks indicate the need of grinding while tamping could eliminate the difference between 15 and 30 m/s.
- Deviation over the range of axle loads.
  Even when the calibration is based on locomotives with high axle loads, the linearity of the system is checked by means of a shadow calibration based on passenger coaches. Furthermore empty tagged freight wagons are used to complete the measuring range.

Above the influence of the track quality on the weight measurement the wheel quality is used to assess the reliability of individual axle weight. This is used to avoid that measured overload situations are a result of bad wheel quality. Therefore it is recommended to combine WIM systems with detection of wheel quality.

3.4 Advisable Track Properties for WIM Systems

Using the bending of the rail, accurate measurements are likely to reach when:

- The track has concrete sleepers.

- The sleeper pads are elastic and contribute significantly to the track elasticity.

- Corrugation is avoided by periodic grinding. An example of the oscillation of the dynamic force at 39 m/s due to corrugated track is given in Figure 12. In this case the sleeper pattern was also worn into the rail exciting the wheel dynamically with an amplitude of about 20 kN, influencing the accuracy of the train weight, and making the assessment of the wheel quality for maintenance purpose impossible.

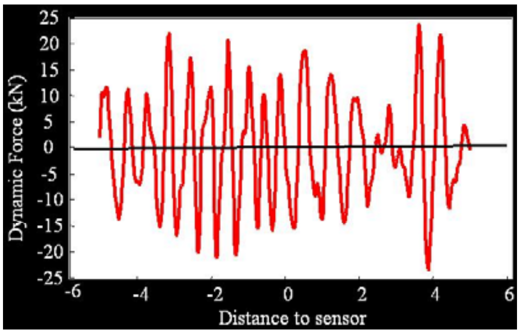


Figure 12 - Influence of Long Wave Corrugation on Dynamic Forces

- The vertical alignment of the track is of such quality that vertical dynamic excitation of the vehicle is avoided, 3 s for the measuring site and 1 vehicle length after (25 m). This demand is fulfilled in the Netherlands in 95 percent of the sites without any additional maintenance.
- The site is on straight track, although this is only needed for a good assessment of the wheel quality.

3.5 Results

With regard to the weight measurement functionality, some results are presented here coming from more than 600 consecutive passages of an electric locomotive, type E-lok1600 (Dutch electrical locomotive, 4 axles 84 tons). As mentioned before, this type of rolling stock is used while it has a well-defined mass and is therefore capable for providing verification data. Figure 13 shows the derived weights.

The measurements are carried out with vehicle speeds between 15 and 40 m/s. It appears that all measurements are within +/- 5 percent of the actual weight. The standard deviation is 1.16 percent, and this is representative a site of average quality.

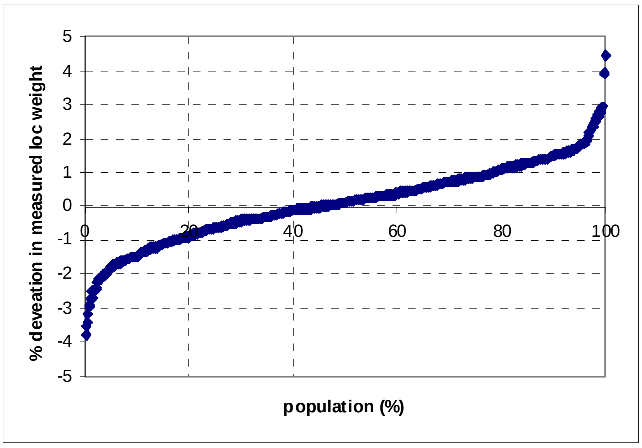


Figure 13 - Deviation of Weight Measurements

4. Conclusions

A compact measuring system for train weight and wheel defects has been build based on four optical sensors, mounted underneath the rail. These sensors measure the vertical bending of the rail and this turned out to be an appropriate quantity for this purpose.

To be able to analyse the measured data, the response of the super structure is analysed using models which allows us to translate measured data into wheel/rail interaction forces.

To guarantee the quality of the measurements it is important to recognise bad track properties, preferably continuously during normal operation. Therefore an auto diagnoses system is implemented.

The system is capable of measuring the train weight with a high accuracy at normal operational train speed. High accuracy is obtained by means of automatic calibration using locomotive with known axle weight as well as passenger trains with variable axle loads.

The system is also capable of determining wheel defects, also in an early stage. The wheel defect detection is both used to assess the wheels for maintenance purposes as to check the validity of the measured axle weight. After implementation of the GOTCHA system, collateral damage like broken springs of the primary suspension no longer occurs and hot axle boxes (wheel bearings) disappeared for 90 percent. This goes on for all bogie parts and finally it results in an increase of the overhaul period, resulting in significant cost reduction. In almost all cases recent measurements of the wheel quality are available and therefore additional measurements for wheel defects in the maintenance shops are cancelled, resulting in another cost reduction for the maintenance of rolling stock.

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QUO VADIS: NOT JUST A MEASURING INSTRUMENT FOR WEIGHTS AND WHEEL QUALITY
THE DEVELOPMENT OF A MEASURING SYSTEM FOR PRORAIL

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Abstract

38 compact measuring system to determine train weight and wheel quality under operational speed. These systems are used in the track access charge system but are also used to optimise infrastructure maintenance. The system uses glass fibre sensors which measures the deflection of the rail during passage of the train. The system is self calibrating using automatic vehicle identification and is combined with information from the traffic control systems.

Keywords: WIM, Weight in Motion, Track Access Charge, Train Weight, Axle Load.

Résumé

38 système de mesure compact visant à déterminer le poids du train et la qualité des roues à la vitesse opérationnelle. Ces systèmes sont utilisés dans le système de charge d'accès à la voie, mais aussi pour optimiser la maintenance de l'infrastructure. Le système utilise des capteurs en fibres de verre qui mesurent la flèche du rail lors du passage du train. Il s'auto-étalonne sur la base de l'identification automatique des wagons et est combiné aux informations issues des systèmes de contrôle du mouvement.

Mots-clés: Pesage en Marche, Poids des Trains, Charge D’axe.

Quo Vadis：Prorail 量測系統之開發

摘要：

本文說明已在使用中之 38 套玻璃纖維感測器量測系統應用於量測列車在運行速度下之重量及輪胎品質，並藉以用在軌道路線計價系統以及軌道設施維修保養的最佳化上。本系統選用玻璃纖維感測器爲原件，其可用以量測當列車經過時鐵道產生之撓度。本系統應用自動車輛辨識進行本身校估，並與交通控制系統所獲得之資訊進行結合。

關鍵字：WIM、動態地磅、軌道路線計價系統、列車重量、軸重

1. Introduction

"Where are you going and carrying what weight?" This is the question that Quo Vadis can help ProRail answer. The question is interesting in the light of New Track Access Charge that as of 01.01.05 is (scheduled) that carriers will be charged for the right to use the Dutch rail network.

This publication will examine the primary objective of Quo Vadis with respect to the Track Access Charge methodology at ProRail (the Dutch manager of railway infrastructure), the Quo Vadis tools employed, and the spin-off of this development.

ProRail is responsible for the management and upkeep of the national rail network and has been allocated the task of determining the usage fee in accordance with the EU directive 2001/14 within The Netherlands. This directive specifies that the track access charge must be cost-related. The major cost item for the railway infrastructure is the superstructure. It has been established from a literature study, which has been endorsed by experts, that the static and dynamic forces that are exerted by the wheels, in particular, are a measure of the maintenance requirements of the superstructure. After extensive market research, development has been started by ProRail in co-operation with NedTrain, the rolling stock manager, to be able to measure these forces in a efficient and effective way. The joint development has led to 2 different applications, namely:

- Quo Vadis (ProRail): a system that is able to measure the static weights of axles and, in addition, to assess the quality of wheels based on dynamic forces.
- Gotcha (NedTrain): a system that is able to assess and monitor the quality of wheels, prioritise repairs and then optimise the operation of NedTrain's various underfloor wheel lathes.

Only the Quo Vadis system is described here. The two systems are based on the same principles and most information is identical as well. The difference between the applications lies in how this information is processed.

2. Legal Framework

The institutional triangle is a well-known concept in The Netherlands (Figure 1). This triangle is represented in the figure below.

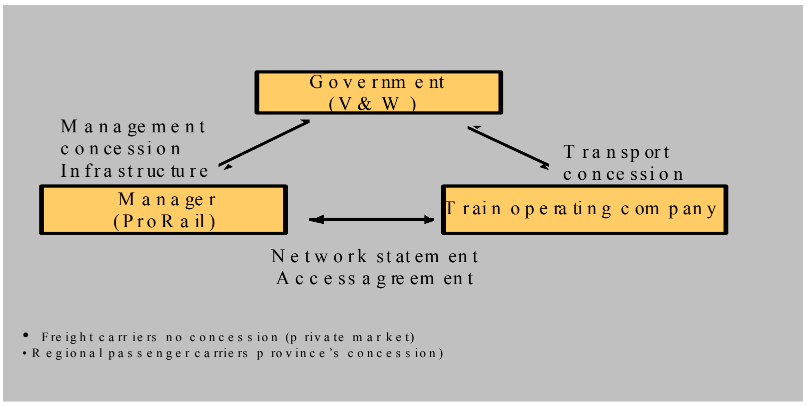


Figure 1

Agreements between the government and the infrastructure manager are laid down in the management concession. In particular, this concerns the functionality of the infrastructure and the performance of the manager with regard to safety and the environment. The transport concession between the government and the passenger carriers includes arrangements on transport punctuality, frequencies and fares. The network statement lists the ways in which the infrastructure may be used. The access agreement identifies the arrangements between the infrastructure manager and the individual railway companies concerning the usage and the quality to be supplied for both the infrastructure and the railway company (including quality of rolling stock).

3. Methodology of the Track Access Charge

The objective of the EU directive is for the carrier to pay for the infrastructure costs it incurs. The underlying principle here is to obtain a fee system for all modes of transport with a methodology allowing comparison. The effect of this will be that the customer (the passenger or shipping company) will choose the most attractive form of transport. In time, societal considerations will also be incorporated into the track access charge. Then the customer will choose by what will benefit society the most. The relatively favourable societal effects of rail transport are expected to lead to a shift amongst modes of transport in favour of rail transport.

The new railway act was adopted by the Dutch parliament's in 2003. This act, which is expected to be in force as of 01.01.05, implements the EU 2001/14EC directive. The act and the directive are fairly detailed in specifying what railway infrastructure costs are to be charged to the carriers. Neither the act nor the directive specify what cost drivers are to be used. It is specified that the costs shall be allocated as fairly as possible. The competition authority will oversee this.

What we are looking for, then, is the best possible parameter for charging for the costs.

Weight is an important cost driver for the superstructure, but is not a factor, or only barely, in wear and tear to the overhead lines or in traffic control. Here the number of trains is more important.
A mixture of train kilometres, tonne kilometres, stops and energy consumption was finally chosen. Train kilometres, stops and energy consumption can be measured using existing systems. Quo Vadis has been developed for weight.

In addition to weight, a second extremely important cause of wear and tear to the superstructure is wheel quality. Worn areas, polygonisation and chipping cause significant wear to the superstructure. The exact effects of these are not yet known.

However, directly applying this to the track access charge is too complex a task. For this reason a bonus-penalty system ('performance scheme') will be implemented, which encourages the carriers to maintain their wheels properly.

For this new measuring system, data handling and processing is also an important consideration. ProRail requires all incoming data to be processed via a central billing system so that each carrier is sent a specified invoice on a monthly basis. To ensure that this process runs smoothly, a software system is currently being developed.

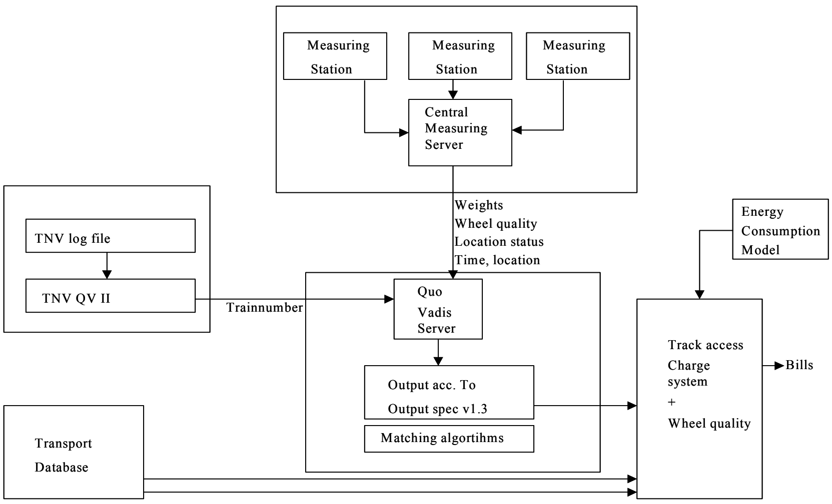
4. The Quo Vadis Measuring System

The Quo Vadis system has been developed by ProRail, Baas R&D and Nedtrain Consulting for ProRail and Nedtrain Services during the period 2000-2004. By now, the system has been deployed in 38 locations on the Dutch rail network. In this way, 80% of all freight and passenger trains will be measured, representing 95% of transport in The Netherlands.

The choice of measuring locations has been optimised using a calculation model provided by CQM. Based upon the forthcoming timetable, CQM completes a calculation on the most useful position for measuring locations. Where applicable, it may be decided to move a measuring location.

4.1 General description of the system

The description of the total system can be illustrated using the following diagram (diagram 1).



The required data is collected and, where applicable, stored for an extended longer period of time (approx. 2 weeks) at the measuring location. Every day the collected information is transferred to a central database. This is where both ProRail and NedTrain get their data for further processing. The Quo Vadis data is combined with the train number at ProRail – this is what is referred to as matching using the matching algorithms. This data is then stored in the database on the Quo Vadis server. The Quo Vadis output is subsequently supplemented with the number of kilometres travelled, the stops at station and the energy consumption.

5. Description per System Module

5.1 Local Installation, Sensor

In the Quo Vadis system measuring takes place using a sensor specially developed for this purpose by Baas R&D in which advanced fibre optic sensor technology is used. The sensor is mounted under the rail and is connected with a reader in a system box alongside the track. The reader generates an optical signal that is transmitted to the sensor over a fibre optic cable. The sensor converts the (minute) vertical deflection of the rail as a result of the passing wheel into a change in the optical signal, which is converted in turn by the reader into a precise electrical signal that is available for further processing (Figure 2).

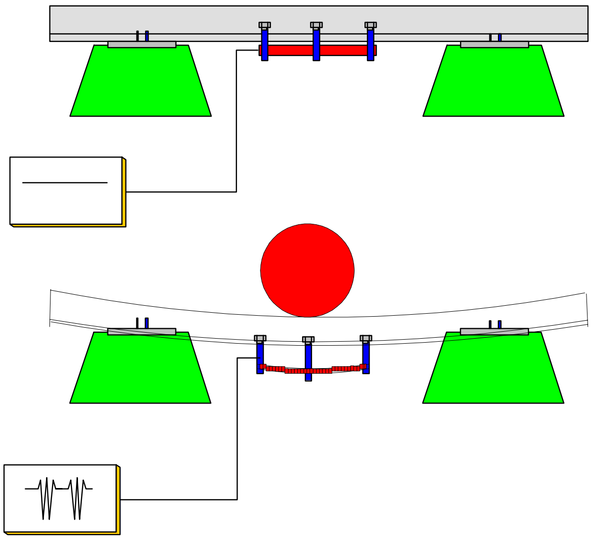


Figure 2 - Operating Principle of the Optical Sensor

The sensor's optical system is housed in a robust metal casing, which is attached to the rail using quick-fit clamps. Thanks to its compact construction, the sensor is resistant to the vibrations that occur in the rail. The reader use the optical signals to check whether the sensor is mounted correctly (Figure 3).

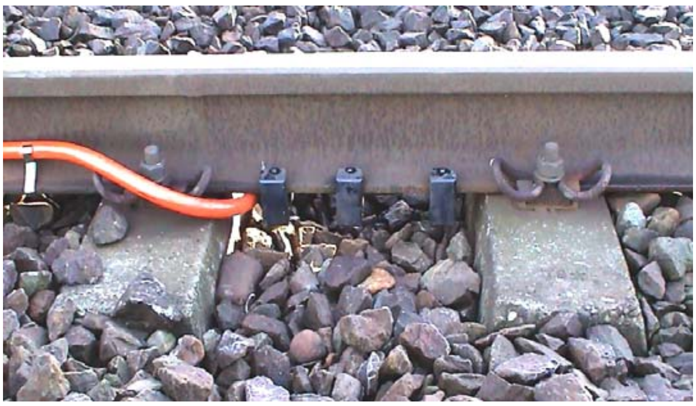


Figure 3 - Sensor Attached to Track

Sensor properties include:

- (dis)assembly without track possession
- durable (low-maintenance)
- regular maintenance of the superstructure possible without removing
- unaffected by EMC from the train, and no EMC emission
- clear measuring signal and high 'signal-to-noise ratio'

The signal generated by the sensor while the wheel passes over it has the following appearance. The axles can be seen on the horizontal axis whereas the vertical axis represents the weight. When a poor wheel passes over, there will be a vibration in the track (see Figure 2).

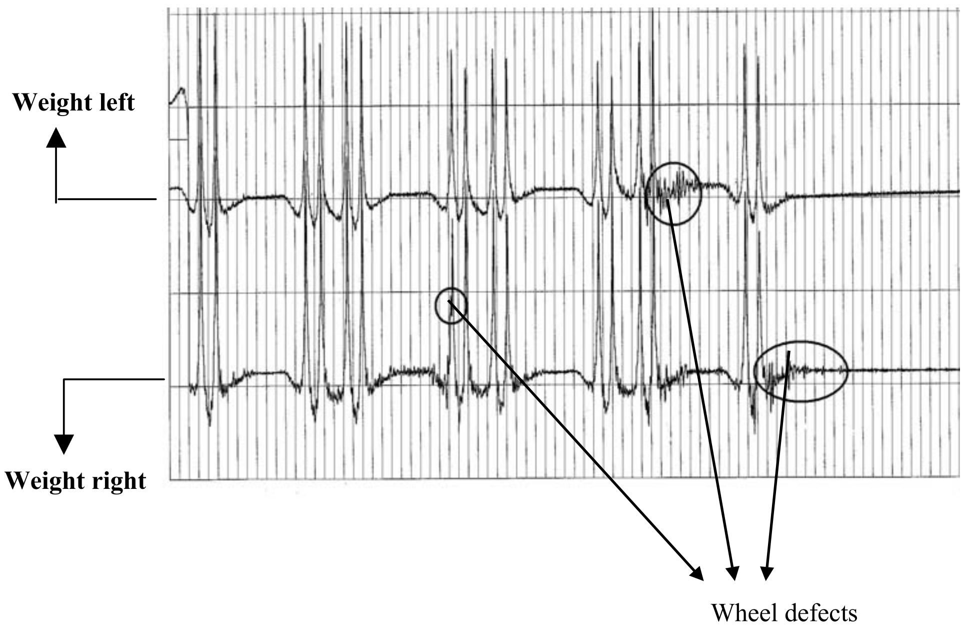


Figure 2 – Sensor Output

This signal does not depend on speed, provided the speed is >40 km/h. The independence at speeds >140 km/h was established using theoretical and laboratory tests.

After extensive testing, 4 sensors per location proved to provide a sufficiently reliable result, also allowing the speed to be simply measured.

The sensor, therefore, provides information about train weight, weight per axle, wheel quality, speed and the number of axles each time a train passes.

5.2 Local Processing Unit

The information is processed in the local processing unit both for the weight measurement and the measurement of wheel quality. The equipment used to measure the deflection of the rail is compact and simple to install, but requires advanced signal processing to determine the quality of the running surface and axle load with a sufficient degree of reliability.

The software required for signal processing, using MATLAB, was developed at Nedtrain Consulting.

The weight of the train can be effectively determined from the deflection of the rail in which the following is taken into account:

- The variation between the stiffness and damping of the superstructure over time, which affects the amplitude of the deflection measurement.
- The influence on the deflection of the rail under a wheel by adjacent wheels as is the case, for example, within a bogie.

When measuring weight, the effects of wheel quality must be eliminated to be able to apply the correct data.

To allow for variations in the infrastructure, each measuring location is automatically calibrated. The regular calibration method for this type of system (also in road transport) is to travel over it with a standardised weight and to adjust the parameters in the system accordingly. On railways we have the fortunate situation that there are many standard weights travelling around. These are popularly called electric locomotives; the advantage of the locomotives is that their weight is known and it does not really vary with time. For example, there is no fuel on board, that is used up during the journey.

By identifying these locomotives by means of a tag (automatic vehicle identification) screwed on to their side, Quo Vadis is able to calibrate and check itself several times a day. Calibration is completed using diesel locomotives on line sections on which there are no electric locomotives. Because these locomotives are subject to some variation in weight based on the fuel tank contents, this calibration is less 'solid' than calibration using an electric locomotive.

In some situations, there aren't even any diesel locomotives available. Calibration is then completed using an average of a number of specific trains.

Each measuring unit is calibrated a minimum of once a day for which the above order is applied.

The method of identifying vehicles by means of tags is not yet used within Quo Vadis for any other applications. Currently the communications equipment is used to be able to generate alerts (excessively poor wheel quality, excessive axle loads). Tags thus represent the constraint used for locating the correct train.

Software is used to analyse the deviation determined in respect of the wheel quality measurement. This analysis makes it possible to determine the nature and seriousness of the defect.

Maintenance is relatively simple, the units are monitored remotely from a central location; only an annual inspection and service is required. Regular track maintenance using machines is possible without removing the measuring unit.

The sensors and, where applicable, the connection boxes are the only things requiring disassembly with screens and when replacing track.

Central Processing Unit

The central measuring server currently retrieves data once every four hours from the local units. For practical reasons involving cost and turnaround time, it was decided to have a complete separation of these measurements from existing control and security systems. This does mean that the data has to be linked with a train number centrally based on time and location.

Tools for Determining Train Numbers and Distance Travelled

In The Netherlands, every train has a unique train number every day. The train numbering methodology works in such a way that a carrier can be derived from the train number. The traffic control system from planning up to operation is entirely based on train numbers. The basis of this traffic control system is a trainnumbertracking system (TNV), whick is filled in automaticly from the planningtools. The TNV log files are collected on a daily basis for Quo Vadis.

Quo Vadis uses specially filtered TNV files to link train numbers and measurement data. ProRail has developed three different types of matching algorithms to handle this. Currently, we achieve a matching rate of 99.6% of the available measurements.

The advantages of train and carrier identification afterwards are:

- Even tagless rolling stock is identified.
- No invoices is submitted to (rolling stock of) carrier A commissioned by carrier B to run a train using a carrier B train number.

Now that the measurement is linked to a train number, this information needs to be supplemented with the distance travelled for each train number on each day. This is a process that takes place separately from the measuring units, in which a second match is made using data from ProRail's transport database. This matching algorithm has also been developed by ProRail in house.

The transport database records all information about scheduled and realised train movements.

6. Results up Today

The measuring units have now been in service for some time and the first results are emerging.

NedTrain/carrier (Gotcha in service since 2002)

- Wheel quality has increased noticeably, whilst repair costs have fallen
- The problems in the autumn (falling leaves) are under control
- The number of broken springs in bogies has fallen by 90%
- The number of hot axles has fallen by 50%

ProRail (Quo Vadis operational since the end of 2003)

- The number of tonnes transported proved to be approx. 22% higher than thought, which partly explained the existing replacement backlog.
- Maintenance strategies have been/will be adapted

Other developments (spin-off)

Other than using Quo Vadis for its primary function, there are a number of extremely useful ancillary functions available for both the train operating company and ProRail.

The data from Quo Vadis together with the information from the TNV log files provide information about the actual use of all infrastructure elements throughout the whole of the ProRail rail network. It is now known for each line section how often, and with what load, trains run over it. This is also known for each set of automatic points, even for each direction and for each position.

Using this data, three categories of points have now been identified, each requiring their own maintenance strategy. By doing this, the small maintenance costs of the points has dropped with 10% (ca. € 2 mln each year).

The application can easily be extended into the following areas. There is currently still too little data to be able to make any substantiated assertions:

- By linking this information to the quality data recorded twice a year using a special inspection train, it is possible to visualise deterioration as a result of use. The data can be linked to fault and object records to be able to establish relationships between usage and faults.
- The data can be used to make better life cycle judgements, to validate cost models and even to question the function of certain sets of points.

With supplementary on-site hardware it is possible to use the Quo Vadis 'infrastructure' to measure noise and/or vibrations. This supplement fits in with the philosophy of 'he who pollutes, pays'. As a pilot, one unit has now been upgraded with noise and vibration measurement facilities, and four more locations will be similarly enhanced in 2004.

The use of Quo Vadis as an alert system in the case of permitted axle loads or dynamic forces being exceeded is currently being prepared. While the technical preparations are being made, the operational realisation will not take place until 2005.

The use of supplementing Quo Vadis with hot-box detection (measuring hot axle bearings) is being researched at the moment.

Automatic vehicle identification also results in new applications. The refuelling depots (there are 20 in The Netherlands) will therefore be fitted with tag readers linked to diesel output.

Only locomotives with tags can use the refuelling depots. Financial accounting is very straightforward.

The latest possibility, which has not yet been explored, appears to be the expansion of QV stations with equipment to determine emissions from trains. Take combustion gases and EMC as examples.

7. Conclusion

This publication discussed the reasons for developing the Quo Vadis system and its key operating principles. In addition, the system proves to have more potential applications than was initially assessed.

ProRail has obtained an extremely valuable instrument in Quo Vadis. It serves to comply with the European directives and the national railway act, of course, but also to manage the infrastructure more effectively.

The whole development, including installing 38 measurement stations has cost € 3,2 mlm for ProRail. The benefits in maintenance of the points only is already € 2 mln / each year. Pay back periode of this development is there fore < 1,6 year.

PERFORMANCE OF A RAILWAY TRAIN WIM SYSTEM

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Graduated from Technical University of Delft, mechanic-cal engineering. Since 2000 responsible for the analysis software of the Gotcha WIM and wheel defect detection system.

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Abstract

In the frame of the Eureka project Footprint, which objective is to develop methods for measuring the vehicle/infrastructure interactions, the companies Baas R&D and NedTrain Consulting have developed a WIM sensor using fiber optic technology. The WIM station is able to estimate the total train weight and the axle loads. The system is also able to detect wheel and local rail defects responsible for the quick degradation of the infrastructure and/or the train. This paper shows the performance in terms of accuracy of this WIM system, assessed using known identified locomotives.

Keywords : Weigh-In-Motion, WIM, train, locomotive, wheel unbalance, maintenance.

Résumé

Dans le cadre du projet Eureka Footprint dont l'objectif est de développer des méthodes de mesure de l'interaction véhicule/ Infrastructure en service, les sociétés bass R&D et NedTrain Consulting ont mis au point un capteur de pesage en marche basé sur la technologie des fibres optiques et une station de pesage capable d'estimer les poids statiques totaux, des groupes d'essieux (boggies) et des essieux de groupe. Le système est aussi capable de détecter les défauts de roue ou de rail localisés impliquant une dégradation accélérée de l'infrastructure ou/et du train. L'article présente les performances du système en termes de précision, calculées avec des locomotives identifiées et de poids connus.

Mots-clés : pesage en marche, train, locomotive, défaut de roue, maintenance.

列車動態地磅系統之績效

摘要

Baas R&D and NedTrain Consulting 兩家公司在"Eureka project Footprint"計畫內以光纖技術發展動態地磅(Weigh-in-Motion, WIM)感測器，前述計畫目的爲發展量測車輛與基礎設施間相互作用之方法。動態地磅站可用以預估列車之總重以及軸重。前述以光纖發展之動態地磅系統則可偵測軌道之瑕疵，此瑕疵爲造成基礎設施以及列車損壞之重要因素。此篇文章藉由探討此一動態地磅系統之正確性進行系統績效之評估，並以已知之列車車頭進行試驗。

關鍵字：動態地磅、列車、列車車頭、車輪不均勻、維護

1. Introduction

The global aim of Footprint is to develop methods for measuring the vehicle/infrastructure interaction. These vehicle/infrastructure interaction generates impacts which can be converted into monetary costs. So, operating companies can be charged for their use of the infrastructure thus providing a basis for charging local, national and transit traffic. Providing engineering-based solutions will help to achieve a political consensus on what is considered a fair charge.

It is important to note that in a lot of European countries, the rail infrastructure belongs to private infrastructure managing companies (which are to be distinguished from the national historical operator). These private companies are responsible for the development, the construction and the maintenance of railways.

A system able to identify the train, to measures its weight in motion and to checks if it is not damaging for the infrastructure, is a useful tool as it is preferably not to stop the train. For maintenance reasons, it is important to detect wheel defects because they are partly responsible for the degradation of the train and of the track.

Another aim of Footprint is to design Weigh-In-Motion specifications for trains based on the COST 323 specification on Weigh-in-Motion of Road Vehicles (COST 323, 1999)

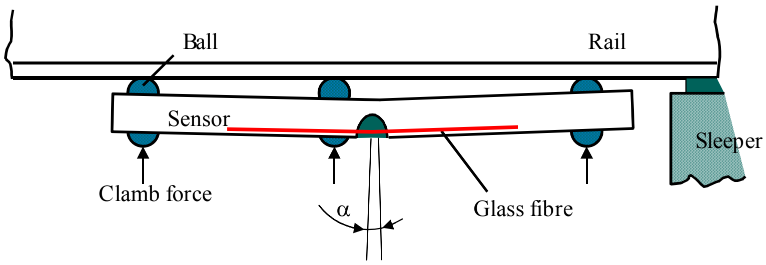
2. System description

NedTrain Consulting and Baas R&D have developed a WIM system in the Netherlands. The system consists of a wayside measuring box with electronics and telecommunication systems for processing and distribution of fibre optic signal from sensors mounted under the rail.

For easy recognition of the rolling stock, the wayside measuring box is equipped with a RFID Tag (Radio Frequency Identification) reader, assuming that the rolling stock is also equipped with RFID Tag's.

The load sensors use fibre optic technology and light attenuation. They have been optimised for measuring the bending of the rail during the pa ssage of the train wheel. The principle of the sensor is given in figure 1.

For the determination of the train weight, axle loads and wheel quality, at least four sensors must be mounted under the track. The sensors are attached two by two (inside leg and outside leg) at a distance of 4.20 m each from the other (see figure 2).



The angle α is measured, and follows the vertical bending of the rail.

Figure 1 - Principle of the sensor under the rail

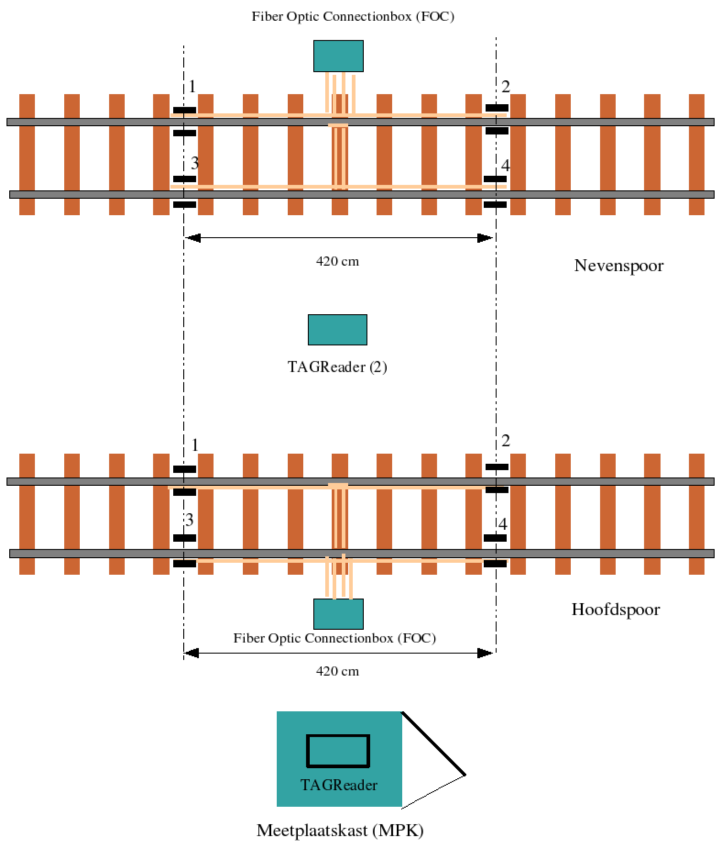


Figure 2 - Typical layout of the measuring system components

3. Experiment description

3.1. WIM site and data

WIM data were received by LCPC for 7 sites on different locations in the Netherlands.

The data files contain:

- the identification number of the measuring station (UnitID)
- the identification number of the rolling locomotive (note TrainID)
- the speed of the train entering the site (VelocityIn)
- the speed of the train leaving the site (VelocityOut)
- the load of each axle of the locomotive measured in motion
- the gross weight of the locomotive measured in motion.

The locomotive static gross weights were known thanks to their identification. The static load of each axle was assumed to be one fourth of the static gross weight. This is a rather raw approximation, which neglects acceleration or breaking forces.

3.2. Test plan

3.2.1. The locomotives

The considered locomotives are electrical locomotives of the series 1700, consisting of 2 two-axle bogies, manufactured by GEC-Alstom. The locomotives are in normal service and are not pre-weighed. However, their gross weights are almost constant and known since they are measured before the locomotive enters into operation. The gross weight is about 800 kN, and thus each axle load is approximately 200 kN.

Figure 3 - Locomotive of the series 1700 of the Netherlands Railways

3.2.2. Sites and speeds

Data were received from 7 sites of the Dutch railway network. Each site and set of measurements is considered as one test. The sites are identified by numbers: 12, 28, 41, 44, 111, 274 and 383.
The measured speeds were between 5 and 40 m/s (18 to 140 km/h) The speed is representative of the normal operational speed in the Netherlands. Most locations are situated such that the change speed trains is small.

4. Results

The accuracy is computed according to the methodology of the European Specification on Weigh-in-Motion of Road Vehicles (COST323, 1999). However, because the accuracy classes were not defined nor calibrated for railways, the accuracy is here quantified with the "delta min" (dmin) values, i.e. the half width of the confidence intervals for gross weights, axle loads and bogie (group of axles) loads. The tests were performed in extended repeatability conditions, because only one type of standard locomotive was involved, with constant static loads but with different speeds. As shown in table 1, the tests were also performed in limited environmental reproducibility conditions, because the test periods extend over a few weeks within the same season, such as the temperature, climatic and environmental conditions vary during the measurements, but no seasonal effect has to be considered. The levels of confidence are specified in the European Specifications, depending on the test plan and environmental conditions, and on the sample sizes. Here they are all comprises between 96.3% and 97.3%. It means that the probability to get a relative error within the interval [-dmin; dmin] is close to 97%.

site number	Measurement period	Number of train passes	Number of outliers	Percentage of outliers (%)
12	09/15/04 →10/18/04	255	8	3,1
28	09/15/04 →10/17/04	385	20	5,2
41	09/23/04 →10/18/04	1105	52	4,7
44	09/15/04 →10/18/04	1404	47	3,3
111	09/15/04 →10/17/04	694	19	2,7
274	09/15/04 →10/17/04	495	10	2,0
383	09/15/04 →10/18/04	241	4	1,7

Table 1 - Measurement characteristics

A Dixon test at 95% confidence level was performed with the data. The computation shows that the percentage of outliers are between 2 % and 5%.

4.1. Accuracy classification by site

The dmin values were computed for each site and each criteria: gross weight, bogie weight and axle load, and are presented in Figure 4. As expected, the dmin are smaller for the gross weights than for the bogies and axles. The sites 274 and 44 gives rather good values for all criteria and especially for the gross weight for which dmin is very low and above all, the ratios between the dmin values of bogies and axles and the dmin of gross weights are as defined in the European Specifications.

Using the European Specifications leads to classify all the sites which is very important for the train manager. Unfortunately, it was not possible to explain the site classification because all the technical characteristics of the site (slope, evenness, skid resistance…) are not known at the present time.

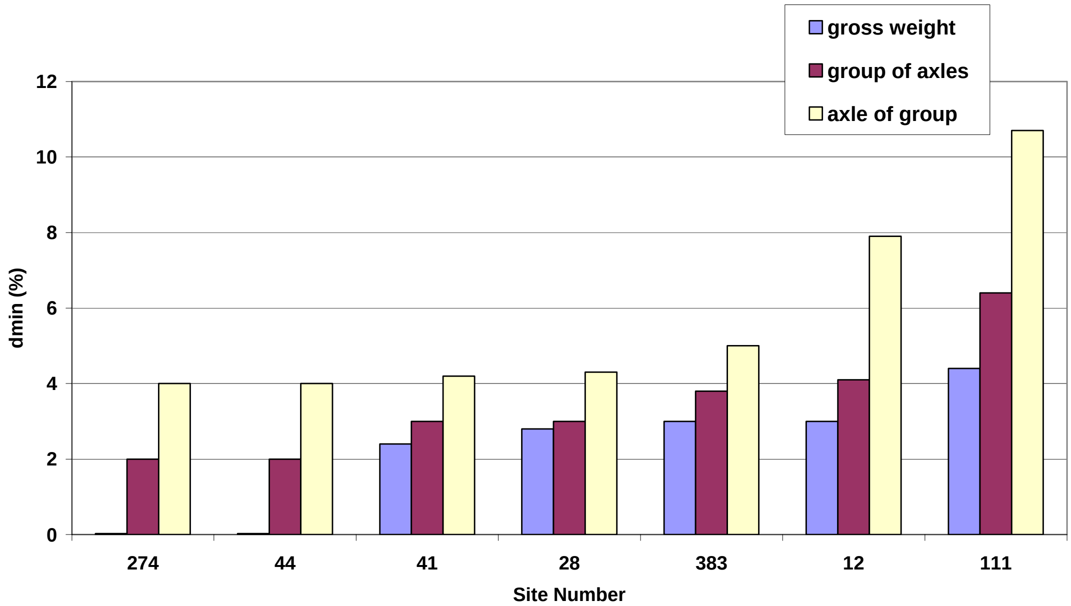


Figure 4 – Accuracy classification by site and criteria (delta min values) without outliers

Site number	Critéria	Number	Mean (%)	Std (%)	Delta min
12	GW	247	0,06	1,35	3,0
	GoA	494	0,06	1,83	4,1
	AOG	988	0,06	3,50	7,9
28	GW	358	0,12	1,11	2,5
	GoA	716	0,12	1,33	3,0
	AOG	1432	0,12	1,91	4,3
41	GW	1040	0,06	1,09	2,4
	GoA	2080	0,06	1,32	3,0
	AOG	4160	0,06	1,85	4,2
44	GW	1344	0,04	0,98	0,0
	GoA	2688	0,04	1,60	2,0
	AOG	5376	0,04	2,23	4,0
111	GW	665	0,73	1,81	4,4
	GoA	1330	0,73	2,75	6,4
	AOG	2660	0,73	4,70	10,7
274	GW	476	0,50	0,99	0,0
	GoA	952	0,50	1,38	2,0
	AOG	1904	0,50	2,05	4,0
383	GW	234	0,43	1,27	3,0
	GoA	468	0,43	1,64	3,8
	AOG	936	0,43	2,16	5,0

Table 2 - Statistics on relative errors in % (r2-II) without outliers

Table 2 shows for each site and each criteria the statistics on relative errors and the delta min values computed. The WIM stations are well calibrated because the bias of the error (i.e the mean value of the relative error) is very low on all sites (lower than 0,7%). The standard deviation are between 1% and 5% whatever the criteria.One can noticed in table 2 that for one site, all the biais on relative error are the same whatever the criteria. This can be shown mathematically because of the relationship between the static gross weigh, group of axle and axle of group. We had considered that the static weigh of a group is half the gross static weigh and the static axle weigh of a axle is the quarter of the static gross weigh.

However, in comparison to the delta min computed on road surface, the accuracies are excellent. For gross weight, the delta min is always lower than 5% and between 0% (the best site) and 4,4% (the worst).

For group of axles, delta min is between 2,0% and 6,4 % and for the axles of group, it is between 4% and 8%. For a group of axles a relatively high delta min is found, but the weight distribution over the locomotive is influence by traction force which cannot be avoided.

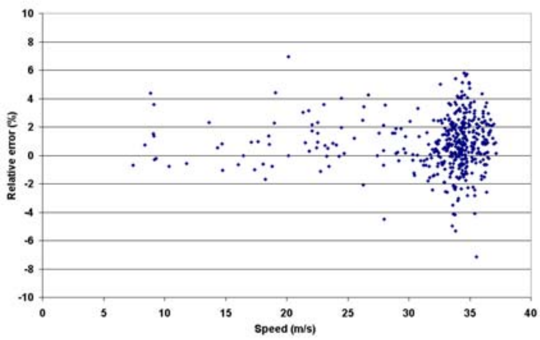
The good results can be explained by the fact that:

- The track properties and especially the rail stiffness have well defined properties and these properties are quite stable in time. The WIM system uses the vertical bending of the rail and this quantity is dominated by the stiffness of the rail itself.
- Most WIM systems are installed on qualitatively good track, but no additional maintenance is performed for the track geometry. Tracks with severe rail corrugation are avoided or the rail is grounded, mainly for the Wheel Defect Detection functionality.

It is not possible to say whether the results are excellent or not because the accuracy is not known of the other systems in the market used under the same conditions. It would be interesting to do such a test in order to calculate the delta min values for railway applications.

4.2. Speed influence on accuracy

In this section, it is tried to show the influence of the speed on accuracy quantified by the delta min value. It is decided to study the speed influence for the worst and best sites which are site 274 and site 111. Figure 5 shows no influence of the speed on the relative error.



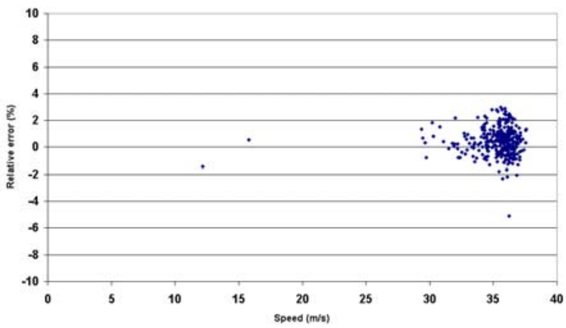


Figure 5 - Relative error for GW for the best site (site 274 – right figure) and for the worst site (site 111 left figure)

5. Conclusion

In comparison to the WIM sensor performance used for weighing road vehicles, railway WIM is excellent because dynamic effects are limited: the rail locomotive is always passing on the same and a qualitatively good track.

Another advantage of the system is that it is possible to detect wheel defects which mainly deteriorate the railway.

However, a railway specification is needed in order to estimate, with accuracy classes, the performance of a system and to help the client to specify which accuracy is needed for its applications.

This specifications could be based on the European Specification on Weigh-in-Motion of Road Vehicles. This specification has to be written within a working group consisting of European railway WIM system manufacturers and railway administration representatives. More WIM data coming from several sites and WIM system manufacturers are needed to assess the accuracy classes.

Acknowledgment

The authors would like to thank Frederic Romboni from LCPC for the data processing he performed for this paper.

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SUMMARY OF SESSION 2 : RAILWAY WIM

Graduated in structural engineering from University of Ljubljana. Expert in bridge assessment and bridge weigh in motion systems. Member of Scientific Committee of all 4 international WIM conferences

Graduated from Ecole Nationale des Télécommunications de Bretagne. Since 2002 with LCPC. In charge of a team doing research in vehicle dynamics, traffic metrology and Weigh-In-Motion of vehicles.

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Introduction

Session 2 focused on the application of weigh-in-motion (WIM) for railways. It was the first time in the series of International conferences on WIM (ICWIM) that a special session was dedicated to railway WIM. Four papers were presented focusing on bridge WIM for railway traffic, on descriptions of GOTCHA, a compact system for measuring train weight and wheel defects, and of QUO VADIS, another measuring system for trains. The last paper dealt with the performance of a railway WIM system.

Synthesis of the papers

Axel Liljencrantz from explained that the *bridge weigh-in-motion (BWIM) principle for weighing trains* is similar to the traditional one used for weighing trucks. The aim of their project was to test performance of BWIM system that used strain sensors embedded into the bridge concrete, rather than the more usual external sensors and to estimate how the railway BWIM system performs. Experiments confirmed that it is easier to perform WIM on railway because the track is always the same (no lateral variation of vehicles) and because there is never more that one train on the same tracks at once. However, two problems may occur: the difference in velocity of difference wagons of the same train can be large. Thus, the speed and acceleration of the train have to be taken into account for the axle load computation. The second problem was the 0.6 meter thick ballast between the loading (wheels) and the instrumentation and the bridge. Consequently, the signal peaks are not very short, which, however, was not presented as a major influence on the results. The bridge itself was a 15 m long integral structure made of self compacted concrete and was instrumented with 4 specially developed resistance strain transducers (force sensor). The “nothing-on-the-road” (with no axle detectors) approach was used. A new algorithm, based on Moses equation, was required. The speed was determined with the phase difference technique and good estimates of real speed were obtained. The standard deviation of speed error was around 5%, with errors of boogie loads around 2 to 3% despite considerable dynamic effects. Mr. Liljencrantz concluded that BWIM is a system which works for railway traffic. Short span integral concrete bridges are particularly appropriate. The future work will automate this system in order to send data automatically when a train has passing the bridge and to classify the system according the COST 323 specification.

H.-J. De Graaf presented the *GOTCHA system* developed for measuring train loads and wheel defects under different speed and loading conditions. Non-round (defected) wheels cause considerable damage on railways, manly by deteriorating its evenness. As wheel are checked

regularly only every 3 months, many of these damaged wheels are detected late. The objective of GOTCHA was to design a monitoring system that will help reducing these damages and associated maintenance costs, both, on infrastructure and on trains. Penalties are applied in cases of overloading or bad wheel use. The system uses glass fiber optic sensors that measure the deflection of the wheel during the train pass. The vertical rail bending is proportional to the boogies weight, with stiffness of the rail very stable with time and temperature. A suitable data processing was developed to estimate wheel defect and train load. High accuracy was obtained (typical standard deviation of the error was 1%), also with the help of self-calibration that was used. At the moment, fifty systems are in operation in the Netherlands and have lead to significant reduction of maintenance costs.
Victor Dolcemascolo presented performance of the *GOTCHA system* according to the COST 323 specification. As not all accuracy classes for such systems have been defined yet, the "delta min" approach was used. WIM GOTCHA data were received from seven sites. The sample consisted of a pre-weighed locomotive passing each of the sites. The test was performed in extended repeatability and in limited environmental reproducibility conditions. It was again confirmed that railway WIM systems perform better than the road WIM system and this is mainly due to the limited dynamic effects. For instance, for the gross weight, the calculations presented the delta min accuracy at around 4%. Mr. Dolcemascolo also emphasised that railway specifications on WIM are needed, They could be based on the COST 323 specifications that were developed for road WIM systems.
M. Den Burman presented the *QUO VADIS* system that measures static axle loads of trains and assesses quality of the wheels based on acquired dynamic forces. Railway is very important way of transport in Holland. They have 22 train operator companies which was one of the reasons why Holland started with railway WIM measurements. The new railway regulation from January 2005 imposed that the minister is still responsible for the infrastructure and the passenger transport. The minister also sets the track access charges that represent the infrastructure maintenance costs for the railway network. These are composed of variable cost paid by the train operator companies and fixed cost paid by the government. The truck access charges are a combination of train-kilometers, stops and its tonnage. A bonus-penalty system is under consideration to encourage the carriers to maintain the wheels properly. Load statistics showed that the actual tonnage was 60% higher than expected and that there are considerable differences between the 4 regions. Furthermore, 10 % of the switches turned out to be heavily loaded, while 50% of them were hardly used. The benefits of using the QUO VADIS system were highly increased quality of the wheels, longer lifetime of the infrastructure and trains, better comfort for the passenger and number of broken springs in bogies fallen by 90%. The system can also estimate number of passengers and indicate which train is overloaded of has a defected wheel. QUO VADIS system turned out to be a good investment in the Netherlands, with the payback period less than 2 years.
The four papers clearly showed that the area of railway weigh-in-motion is much more developed that might have been concluded from the inputs of the first three international WIM conferences. Clearly, the benefits of using them are considerable, which has been proven by the stake holders that use them.

Discussion

Eugene O'Brien from the University College Dublin had some doubts about the resistance of strain gauges used for Railway Bridge WIM and wondered why instrumenting a bridge when you can instrument a rail?

Raid Karoumi, a co-author of the first paper explained that the sensors are made of strain gauges glued on a steel bar, which have proved very durable. A Liljencrantz added that the method used was reasonable accurate, maintainable and cheep but more comparisons with other methods are needed to give a precise answer. The method itself was selected because of the profession background of the authors in bridges.

H.-J. De Graaf noticed that the advantage of railway instrumentation is that it detects the wheel defects, which should be difficult using BWIM. Mr. Liljencrantz agreed that that high frequency measurements needed to detect wheel defects would be difficult to measure with BWIM because on some bridge types the dynamic effects are small and because the bridge are stiff. A solution is to add an accelerometer to detect the high frequencies. Tests already performed proved gave very good results. H De Graff commented that using accelerometers combined with BWIM instrumentation would still cause difficulties identifying the wheel that is defected. R Karoumi disagreed by saying that localization should be possible but that more test are needed in order to quantify the error.

V Dolcemascolo asked a question about calibration of the GOTCHA system. H. De Graff indicated that the self calibration procedure is using the gross weight of the known locomotive as the reference value. Number of passengers can be determined based on the morning trains that are very full or the very late ones that are practically empty.

A. Žnidarič wanted V Dolcemascolo to explain what are good site and bad site. Mr. Dolcemascolo could not answer because he has not received the site infrastructure characteristics. He supposed that the Railway WIM performance depends on the slope, evenness and skid resistance of the railway. It would be interesting to correlate site characteristics and WIM performance. H De Graff shared his experience of one site located 30 meter away from a level crossing. This caused vertical excitations of the trains and, consequently, many scattered results.

A. Žnidarič wanted to know if GOTCHA system was unique in Europe. According to H. De Graff it was not but the other systems available on the market are very expensive. They give similar results but the sensor technology or signal processing are different. At this time, only Holland has completed a network of Railway WIM systems.

B. Jacob added that partners of the FOOTPRINT project have initiated the design of specification on high speed WIM for railways. However, the group in people involved into this issue in FOOTPRINT is very small and people working on railway WIM are kindly invited to join it.

Chris Koniditiotsis was wondering about the purpose of the truck access charge and about attributing the infrastructure cost to he individual carrier. The question was should these infrastructure costs repay what is currently spent for operation and maintenance of the rail network or what should be spent to maintain the rail network? M. Den Burman answered that at this moment the infrastructure costs are defined based on what is currently spent on operation or maintenance of the rail network.

SESSION 3 :

WIM DATA QUALITY, APPLICATION TO TRAFFIC MANAGEMENT AND ROAD SAFETY

Chairperson: Bernard Jacob
Co-chair: Chris Koniditsiotis

DETERMINATION OF THE ENVIRONMENTAL FOOTPRINT OF FREIGHT VEHICLES

      

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Abstract

The movement of additional goods associated with a single market in Europe will increase freight traffic and the resulting road maintenance costs. To reduce this impact, a better understanding of the dynamic interaction between freight vehicles and the infrastructure is required. The European cooperative project Eureka Logchain Footprint E!2486 aims to develop an innovative and cost effective method to identify road and rail vehicles by means of their environmental "footprint" as characterized by dynamic load, noise, ground borne vibration and gaseous emissions induced by the vehicle. This paper presents the Swiss contribution to this project and specifically, the novel Footprint monitoring site on the A1 motorway. This Footprint monitoring site will measure in addition to the above parameters deformation, humidity and temperature at different depths of the pavement. Furthermore the novel stress in motion (SIM) sensor Modulas is discussed.

Keywords: WIM, Weigh in Motion, Stress in Motion, SIM, Eureka, Footprint, Modulas, Acoustics.

Résumé

L'augmentation des transports de fret qu'implique le Marché Unique va accroître les charges pondérales du trafic et provoquer par là une augmentation des frais de maintenance. Afin de réduire cet impact, il est nécessaire de mieux comprendre les interactions dynamiques entre les véhicules de transport de marchandise et l'infrastructure. Le projet de coopération européenne Eurêka Logchain Footprint E!2486 a pour but de développer une méthode innovatrice pour déterminer les coûts induits par les transports au moyen de leurs "empreintes" environnementale caractérisées par la charge dynamique, le bruit, les vibrations induites dans le sol et les émissions gazeuses.Cet article présente la contribution suisse à ce projet et plus particulièrement le nouveau site de monitorage sur l'autoroute A1. Sur ce site, le monitorage des véhicules s'étendra, en plus des paramètres cités plus haut, aussi aux paramètres des déformations, de l'humidité et de la température à différentes profondeurs. De plus, les nouveaux modules capteurs des contraintes en marche (stress in motion, SIM) sont discutés.

Mots-clés : Pesage en Marche, Contrainte en Marche, SIM, Eurêka, Empreinte, Modulas.

貨運車輛環境足跡之訂定

摘要：

在歐洲，單一市場引發之額外之貨物運送將會增加貨運交通量及其衍生之道路維護花費。為減少上述衝擊，必須對貨運車輛及其與公共基礎建設間之動態互動關係進行更進一步的瞭解。歐洲一項合作計畫 "Eureka Logchain Footprint E!2486" ，目的為發展一項用以辨識道路及鐵路車輛之創新且符合成本效益的方法。上述方式係藉由車輛本身所留下的環境"足跡"進行辨識，包含該車輛動態載重、噪音、地表產生的震動以及氣體的排放等。本文將針對瑞士對此項研究計畫的貢獻以及 A1 高速公路上研發的"足跡"監測站進行說明。此一監控站除可用以量測上述參數外，另有撓度、溼度以及溫度在道路不同深度的變化。本文並將針對新式動態應力 (stress in motion, SIM) 感應器進行更進一步的討論。

關鍵字：動態地磅、動態應力、足跡、模數、音質

1. Overview of the Eureka Logchain Footprint Project

1.1 Partnership and Objectives

The European cooperative project Eureka Logchain Footprint E!2486 aims to develop an innovative and cost effective method to identify road and rail vehicles by means of their environmental "footprint" as characterized by dynamic load, noise, ground borne vibration and gaseous emissions induced by the vehicle. The goal is to relate this footprint to the cost of maintaining the infrastructure. The project has currently 27 partners from seven European countries. In summary, the project is innovative in the following ways:

- Use of novel data acquisition systems comprising of sensors or measuring techniques
- Identifying which vehicle types produce greatest vehicle/infrastructure interaction
- Identify policy options which are cost effective to reduce interaction at source
- Make direct comparison between road and rail transport modes

Various phases of the project address a wide range of factors from monitoring and modeling to cost analysis. An important part of the project is monitoring of the vehicle infrastructure interaction and measuring the specific parameters listed above in a reliable, reproducible and costs effective manner. To this end two prototype Footprint Monitoring Sites (FMS), one on the road and one on the rail will be used. The prototype rail Footprint station is located in Zevenhuizen in the Netherlands. This is a fully functional Footprint station using fiber optic rail Weigh in Motion (WIM), vibration and acoustic sensors (Moor, 2003). In the Netherlands 90% of rail vehicles are tagged and are monitored at 40 rail WIM stations.

The prototype road Footprint station will be built in spring 2005 in Canton Aargau in Switzerland on the major east-west motorway A1 between Zürich and Bern.

2. Participation of Switzerland in Footprint

Vital synergies were brought together in Switzerland in order to make a significant contribution to all phases of this project at the European level. Three laboratories At Empa, Road Engineering/Sealing Components, Electronics/Metrology and Acoustics, three federal departments (Swiss Federal Roads Authority, ASTRA, Swiss Agency for the Environment, Forest and Landscape, SAFEL/BUWAL, Federal Office of Transport, BAV) and two private firms (Kistler, RTSC) are partners in the project. Six work groups, listed below, have been formed to address the multidisciplinary problems addressed by Footprint.

2.1 Work Group Modeling

The objective of this Work Group is the computer simulation of road/vehicle interactions to establish damage to infrastructure. The models which would form the basis of the work are from the project DIVINE (DIVINE, 1998) for roads. The models will be used to explore the range of parameters identified in the measurement phase of the project and to predict the influence of vehicle and suspension. This phase of the project is still at its initial stage. Further details will be published elsewhere as they become available.

2.2 Work Group A1- Monitoring site

The first prototype road Footprint station in Europe (Figure 1) will be built on the A1 motorway on a flexible asphalt pavement 3km from the current Empa monitoring site (Raab et al., 2005). In parallel, ASTRA is building a standard WIM station covering all four lanes using quartz-crystal WIM sensors (Doupal et al., 2002). Furthermore, a static weighing station as well as video cameras for vehicle identification will be installed.

The Footprint station will be 6m from the last WIM sensor on the slow lane in the direction Zürich-Bern. In addition to the prescribed Footprint parameters of dynamic load, vibration and noise also temperature, deformation and humidity at different depths of the pavement will be monitored. Gaseous emissions are not measured in situ and are not part of this monitoring site. Further details regarding the measurement of gaseous emissions are under discussion with other European partners. The deformation sensors are based on the magnetostrictive principle (Anderegg et al., 2002). Accelerometers will be placed 4cm below the pavement. Additionally one accelerometer will be placed on the side of the road at the same location as the microphone. The main purpose of these two sensors is comparison to rail emissions and their location is based on the ISO standards, 7.5m from the centerline of the slow lane.

An important part of this project is the installation of two prototype stress in motion (SIM) sensor, Modulas that deliver the tire footprint in terms of vertical contact pressure between tire and road surface, as discussed in section 2.3.

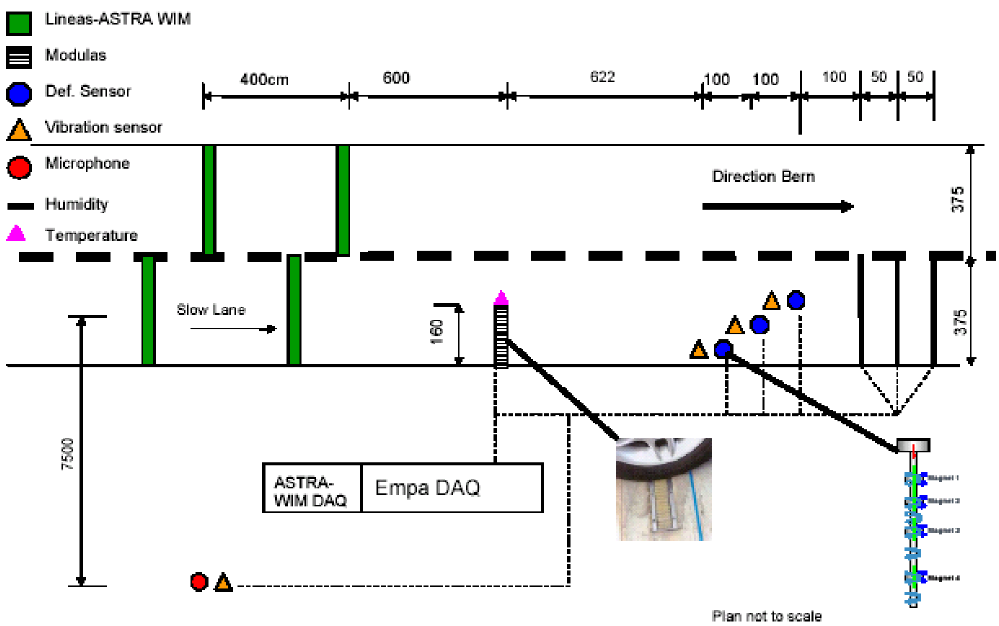

Figure 1 - Architecture of the WIM Station and the Road Footprint Monitoring Site

2.3 Work Group Modulas

The Modulas sensor (Figure 2) is a novel prototype SIM sensor, developed in Switzerland which will be placed on the road FMS. In addition to the standard parameters delivered by WIM sensors, it will be used to improve the methods to analyze the wheel load influences on the infrastructure. It promises to become an efficient investigative tool as the tire force distributions can be measured in real time with a high spatial resolution at motorway velocities. It has been pointed out by several researchers that the effective contact stresses between the tire and the road/pavement surface are not known and are not used effectively in design and analysis procedures (De Beer et al., 1999; Doupal and Gysi, 2002).

With this reusable sensor, it is possible to measure the forces resulting in excess damage to road surface as vehicles cross and to investigate the part they play in the formation of ruts and cracks.

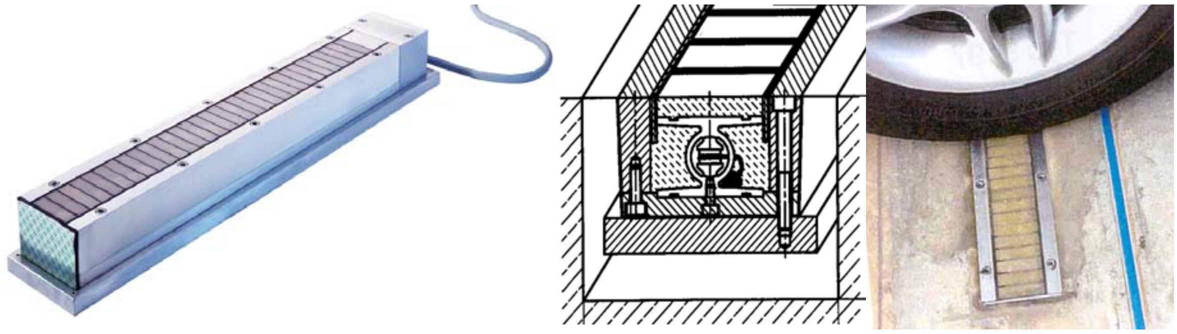

Figure 2 - Stress in Motion (SIM) Sensor Modulas, Left, Schematic, Middle and Sensor Placed in the Pavement, Right

In order to measure the dynamic wheel load forces in more detail by determining their spatial distribution, a segmented quartz sensor was developed on the design base of the Lineas quartz sensor (Doupal and Gysi, 2002). Set flush with the road (Figure 3), the sensor measures the forces by 32 separate sensor segments as individual channels. It is capable of measuring the vertical forces exerted between tire and pavement during vehicle crossing with a spatial resolution of 15mm. The measuring area per force sensor is 14.5 x 50 mm. To de-couple the horizontal forces in the pavement the sensor elements are protected from lateral forces by a special elastic material. For each channel, the system measures the vertical force (F) with a sensitivity of 2.66mV/N. The Modulas system specifications are:

- The maximum vertical force per channel is 1400N with a resolution of 10 N.
- The operating temperature range is from -30°C to +60°C
- The sensor is used preferably with the 32 channel charge amplifier
- The sensitivity deviation is less than 1% for a temperature difference of 50K
- Cross-talk with an adjacent sensor element (channel) is less than 2% of the signal transmission.

The measurement principle and calculation of tire contact pressure, p within the measured area of the tire latch or contact area was discussed by (Doupal et al., 2002). The pressure distribution is calculated from the force using:

$$P_i = \frac{F_i(t)}{v.t_M.B_S} \quad (1)$$

where,

v	Velocity, m/s
B_s	Sensor width (=0.015m)
t_M	Measuring time interval, s
$F_i(t)$	Force distribution at time t
$P_i(t)$	Pressure distribution at time t

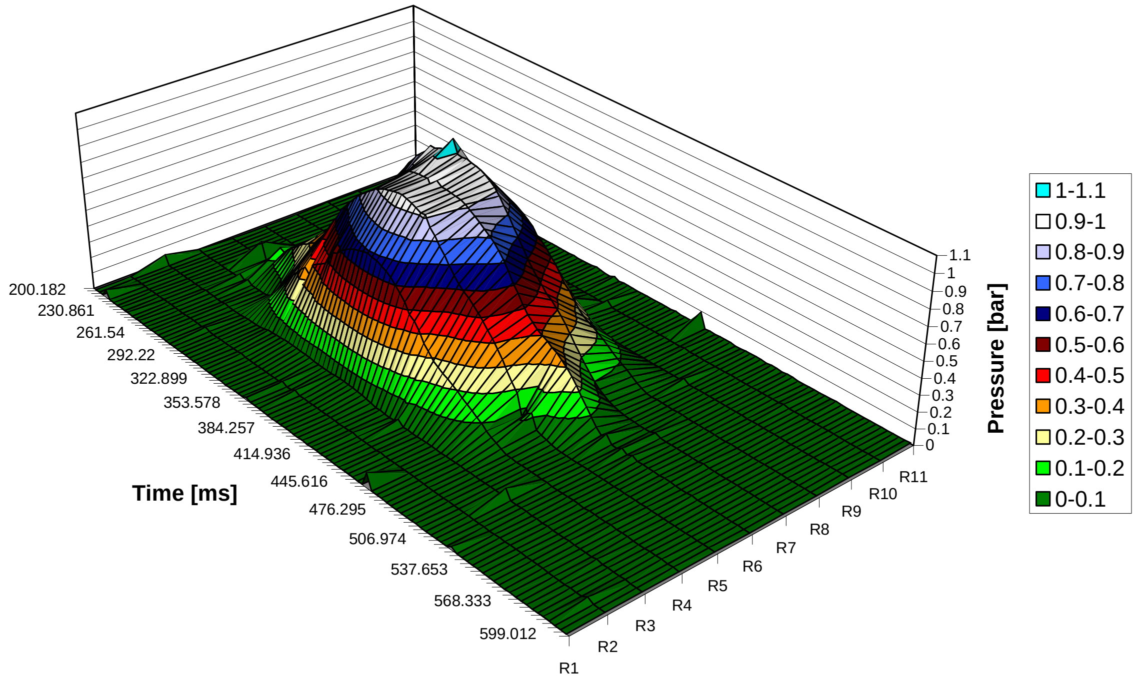

Figure 3 - Pressure Distribution (bar), of the MMLS3 Load Simulator on the Modulas Sensor. Tire Pressure Set at 6bar, Speed at 9km/h and Axel Load at 2.1kN

Preliminary laboratory experiments with Modulas using the Model Mobile Load Simulator, MMLS3 (Gubler et al., 2004) were conducted. Sample of the results shown in Figure 3 are for a speed of 9 km/h, axel load of 2.1kN and tire pressure of 6bar for a Vredestein 400-4, V76 tire . These preliminary results show that the sensor has a potential of being a promising tool for pavement designers as a significant difference in stress distribution under the tire can be seen for over/under inflated tires (Figure 4). As shown by (De Beer et al., 1999), in such cases maximum vertical stresses can occur at tire edges that were sometimes more than 2 to 3 times the inflation pressure of the tires. Further details of the laboratory experiments including accuracy and reliability and first field results at motorway speeds will be reported as they become available elsewhere

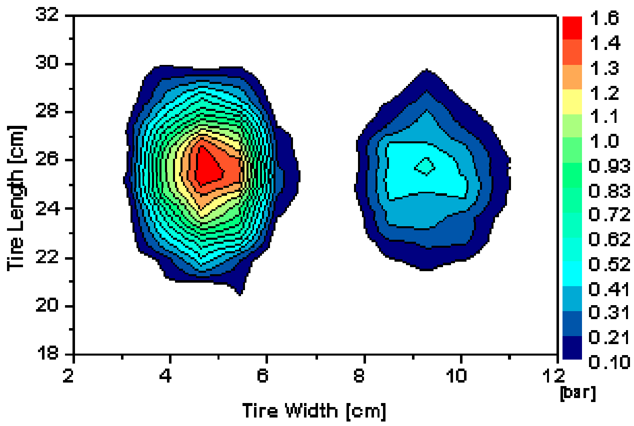

Figure 4 - Example of Isobars for the Same Tire when under-and over- Inflated (Doupal '02)

2.4 Work Group Acoustics

The acoustical characterization of single road vehicles is based on signal attributes of the sound pressure measured at a microphone. It is desirable to use attributes that are robust, widely accepted and easy to evaluate. Therefore the acoustical characterization used here is based on the EN ISO 11819-1 standard which describes a procedure to measure single pass-by events of road vehicles as maximum levels with frequency weighting A to take into account the frequency dependent sensitivity of the human ear and time weighting Fast (125ms) for the moving average.
The main problem of the measurement is the possible disturbance of acoustical emission by neighbor vehicles. To avoid measurement errors it has to be assured that before and after the pass-by of the investigated vehicle the sound level drops 6 dB below the maximum value. Furthermore a significant influence of the measured maximum level originating from other vehicles that are passing by should be avoided. This claim can be substantiated as a condition that there is no other vehicle than the vehicle of interest within a time frame of +/-1 second.

Preliminary measurements at a Swiss highway with two lanes in each direction show that the percentage of valid measurements depends strongly on traffic density (Figure 5). For 500 vehicles/hour in one direction about 70% of the measured values were valid. The increase of traffic density to 1000 vehicles/hour lowered the percentage of valid measurements to 40%. Within the project different strategies as for example a mathematical compensation of the disturbing influence of neighbor vehicles will be investigated to increase the number of valid measurements.

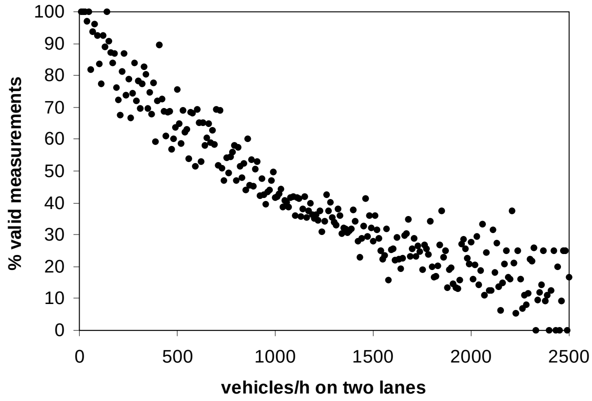

Figure 5 - Percentage of Valid Single Vehicle Measurements as a Function of Traffic Density in Vehicles/hour on Two Lanes Heading in one Direction

2.5 Work Group DAQ

All sensors identified in the previous sections have to measure at the same time, i.e. approximately 100 channels need to be recorded simultaneously. Figure 6 gives an overview of the planned DAQ. Analog and digital signals with quite different dynamics are processed using commercially available electronic devices. The range includes quasi static temperature records and the dynamic measurement of 64 MODULAS-channels for the wheel load with a sample rate of 16 kHz for truck speeds of up to 100 km/h. To gain readout speed for the wheel load measurements data will be stored binary and calculated in an offline process.

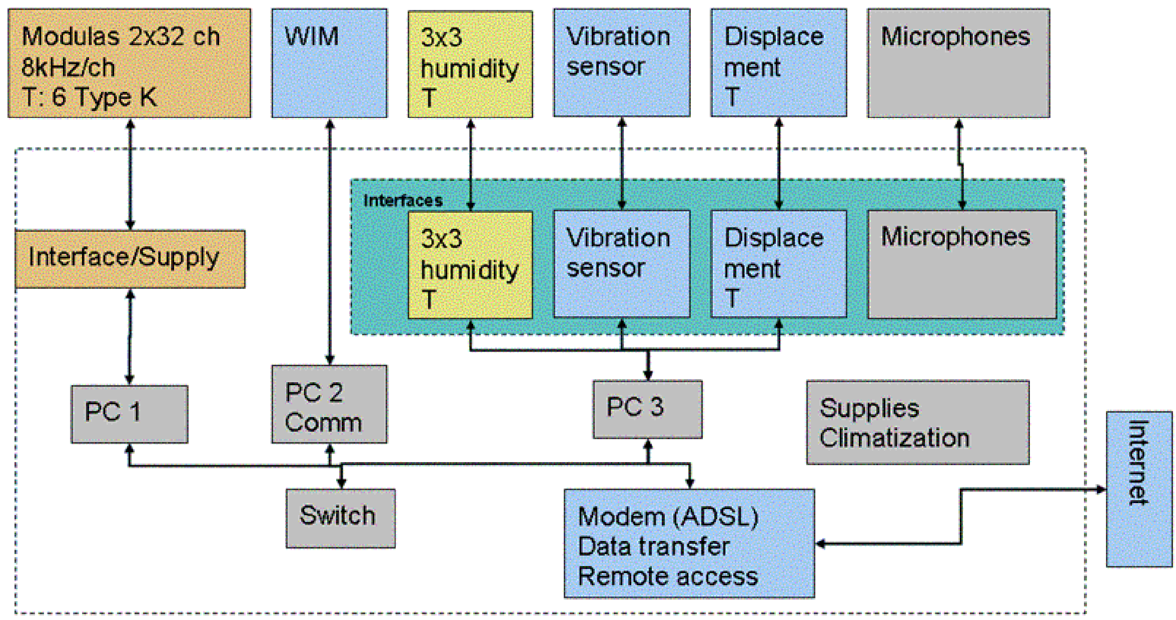

Figure 6 - Overview of the DAQ

2.6 Work Group Policy Options

In this work group representatives of ASTRA, BUWAL and BAV will cooperate with other European partners to use the results of measurements from the monitoring sites as well as modeling to identify policy options which are cost effective to reduce interaction at source and make direct comparison between road and rail transport modes. An important part of this work group is the identification of environmentally friendly vehicles and infrastructure and to produce European labels to identify vehicles and infrastructures as such.

3. Summary and Initial Conclusions

It is apparent that freight vehicles have a significant effect on the environment including the infrastructure. To facilitate the implementation of the prevailing European policy that charges should be related to use, common methods of estimating costs induced by transport have to be developed. Therefore the development of a consistent method of measuring the dynamic interaction of freight vehicles with the infrastructure is vital. This project following the guidelines of the Eureka Logchain Footprint, proposes methods to measure this dynamic impact. In cooperation with other European partners the input from the monitoring sites in Switzerland and the Netherlands will be used to identify environmentally friendly vehicles as well as to estimate costs induced by freight vehicles. This project suggests that WIM technology alone is an important part but is not sufficient for identifying the effect of vehicles on the environment. When addressing issues such as intermodality, the overall effect of freight vehicles should be considered.

Results of preliminary laboratory experiments with Modulas, show the sensor being a promising tool for pavement designers. These results also show that a significant difference in pressure distribution under the tire can be seen for over/under inflated tires which should be used in pavement design.

Measurement of the acoustic emission of single by passes is possible if disturbing influence of neighbor vehicles is investigated to increase the number of valid measurements.

Acknowledgements

This project has been possible by the financial support of Empa, the Swiss Commission for Technology and Innovation (CTI), Swiss Federal Roads Authority (ASTRA), Swiss Agency for the Environment, Forests and Landscape (SAFEL, BUWAL) and material support of Kistler Instruments AG, Switzerland and SIKA AG, Switzerland. The authors would like to thank Dr. R. Mayer, Eureka Logchain Footprints project coordinator for his continuous support and encouragement.

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VEHICLE CLASSIFICATION – A NEW APPROACH

  

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Abstract

Overloaded vehicles cause great damage to the roads. The *Weigh-in-Motion* project of the Dutch Ministry of Transport intends to reduce the number of overloaded vehicles on the Dutch roads. In order to detect overloaded vehicles automatically, the axle loads of passing vehicles are compared to the legal limit. Since the legal limits differ for different types of vehicles or axles, it is critical that vehicles are classified correctly. Analysis of a sample showed that the existing algorithms could not, or incorrectly, classified 17% to 30% of vehicles. Consultancy company CQM developed an innovative classification method with an error percentage of merely 3%. This paper describes this method.

Keywords: Weigh-in-Motion, Vehicle Classification, Algorithm.

Résumé

Les véhicules en surcharge occasionnent des dégâts considérables sur les routes. Le projet *Weigh-in-Motion* du ministère des transports des Pays-Bas a pour but la réduction du nombre de camions en surcharge sur les routes des Pays Bas. Afin de détecter automatiquement les véhicules surchargés, les forces d'impact d'essieux des véhicules sont comparées avec les limites légales. Comme les limites sont différentes par type de véhicules ou d'essieux, il est très important que les véhicules soient classés correctement. L'analyse d'un échantillon avec les algorithmes actuels, prouve que 17% à 30% des véhicules sont pas ou incorrectement classifiés. CQM a développé une nouvelle méthode de classification innovatrice, conduisant à un coefficient d'erreur de 3% seulement, et décrite dans ce papier.

Mots-clés: Pesage en Marche, Classification de Véhicules, Algorithme.

新發展之車輛辨識方法

摘要：

超載車輛往往會對路面造成嚴重的破壞。一項荷蘭交通部進行之動態地磅 (Weigh-in-Motion, WIM) 研究目在於的降低荷蘭道路上的超載車輛。爲了自動偵測超載車輛，將通過車輛之軸重與法令限制值進行比對。但由於法令限制值隨著車輛及輪軸配置形式之不同而改變，因此如何正確的進行車輛分類 (vehicle classification) 爲一重要關鍵。分析樣本後發現目前的演算法其誤差率達 17%~30%。顧問公司 CQM 發展了一套創新之車輛分類方法，其錯誤發展比率僅 3%。本文針對上述分類方式進行說明。

關鍵字：動態地磅、車輛分類、演算法

1. Introduction

In 2001 the Road and Hydraulic Engineering Institute (DWW) of Rijkswaterstaat (the National Road Administration in the Netherlands, part of the Ministry of Transport, Public Works and Water Management) built six Weigh-in-Motion (WIM) systems on the Dutch highway network. These systems are used for pre-selection of overloaded vehicles, collecting data for overload prevention actions and road management statistics.

To ensure the functioning of the WIM system it is essential that axle loads of passing vehicles can be compared to the legal limits. These legal limits differ depending on the type and configuration of the vehicle. It is therefore crucial that vehicles are classified correctly when passing a WIM location. In addition to law enforcement these data are used to analyse the use of the infrastructure, which only increases the need for a correct classification.

Currently there are two classification algorithms in use on the Dutch highway network. They both use axle separation. The original algorithm, which is referred to as *Euro13*, was supplied with the Marksman roadside equipment. The second, which was in use until early 2004, is an adapted version of the *Euro13* algorithm; this algorithm will be referred to as *WIM-NL*. In addition to these two algorithms there is a third algorithm, which was developed and is being used by the Dutch province of Zeeland. This algorithm has yielded results similar to the *WIM-NL* algorithm.

2. Data

To rate the performance of the existing algorithms and to test any new algorithm, consultancy company Centre for Quantitative Methods CQM was provided a dataset containing 1691 vehicles. The data comprises pictures (see Figure 1) of all vehicles as well as the speed of the vehicle, vehicle length, axle count, axle loads, and axle separations All these vehicles were then classified by eye to obtain the true class, as well as being classified using each of the three algorithms.

Figure 1 - Sample Photograph

Prior to any analysis, the data was split into two. This was done to assure that a new algorithm would not be favoured merely by the fact that it was being evaluated using the same data used to tune it. The first half can thus be viewed as a training set, the second as a verification set.

3. Existing Algorithms

3.1 Vehicle classes

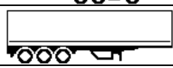
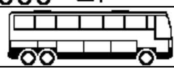
There are a large number of possible vehicle class definitions. The standard class definitions used by the Marksman roadside system are referred to as the *Euro13* classes. These classes distinguish between different types of vehicles (e.g. a Truck or Bus), different configurations (with or without trailer) and different number of axles. A *Euro13* class may be an aggregation of several of these. DWW has defined its own classes. These classes do not aggregate and are therefore more accurate. Each part of a vehicle is identified by a letter as shown in Table 1. The combination of two letters can be used to identify a vehicle combination by its base class, as shown in Table 2. Depending on the level of information required, these base classes can be refined by including axle count information. A truck with two axles would be labelled as V_2. The tractor/semi-trailer shown in Figure 2 would be labelled as T_3O_3, since both the tractor and the semi-trailer have three axles.

Figure 2 – Subclass: $T_{12}O_3$

Figure 3 - Subclass: $T_{12}O_{21}$

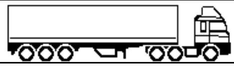
One final refinement can be added to this classification specification. A subclass for a vehicle component can be defined as a single letter (as above) suffixed by one index of each group of axles, where the value of this index indicates the number of axles in that group. The tractor shown in Table 1 has a single axle at the front and a pair of axles at the rear would thus be classified as T_{12}.

Table 1 - Base classes

	Base Class	**Graphical Representation**
Truck	V	
Trailer	A	
Tractor	T	
Semi-trailer	O	
Bus	B	

Using the same logic, the tractor/semi-trailer in Table 2 would be labelled $T_{12}O_3$. It is important to go to this level of detail since it is the only way to distinguish a $T_{12}O_3$ (Figure 2) from a $T_{12}O_{21}$ (Figure 3). In the first case Dutch law permits a maximum load of 7 metric tons on each of the trailer axles; in the latter 8 tons is permitted on the first two axles, since they form a group of two axles, and 10 tons is permitted on the third axle. For a comprehensive definition of the DWW vehicle classes, see Van Doorn (2000).

Table 2 - Possible configurations

	Base Class	Graphical Representation
Truck – Trailer combination	VA	
Tractor / Semi-trailer	TO	
Bus – Trailer combination	BA	

To analyse the performance of the different algorithms a common set of vehicle classes should be used. For this purpose the Euro13 vehicle classification table is used.

3.2 Euro13 Algorithm

The *Euro13* classification algorithm is included as standard in the Marksman roadside system. It classifies vehicles solely on their axle separations. The algorithm is based on a flow diagram approach. If a set of axle separation conditions is met, it is classified as type *a,* if they are not met, the conditions for type *b* are checked etc. If none of the conditions are met the vehicle is classified as *other*. Since the boundaries set in each of the conditions are firm, this approach is particularly sensitive to measurement errors.

Table 3 lists the true vehicle class against the classification as computed by the *Euro13* algorithm for the training set. If all vehicles had been classified correctly by *Euro13* all entries should lay on the diagonal. All off-diagonal elements should thus be viewed as being erroneous. In the training set 250 vehicles are classified incorrectly, which corresponds to 29.7%. For the verification set the corresponding figures are 269 and 32% respectively. Two main problems are that the algorithm classifies many two axle trucks (*Euro13* class 2) as busses (*Euro13* class 12). In addition it classifies many vehicles as *other* (*Euro13* class 13).

Table 3 - Training set, 29.7% classified incorrectly

	euro13													
TRUE	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
1	27	40			16		6					1	4	94
2		76										110	7	193
3			29									3		32
4				12						1			5	18
5					51			1					3	55
6					2	13				9			2	26
7					1		50						3	54
8					6			124						130
9									158				18	176
10										2				2
11											15		4	19
12		1	7									23		31
13													13	13
Total	27	117	36	12	76	13	56	125	158	12	15	137	59	843

3.3 WIM-NL Algorithm

The *WIM-NL* algorithm is the modified version of the *Euro13*. The *WIM-NL* algorithm differs from the *Euro13* in that the axle separation bounds used as criteria for the different classes have been adjusted. In addition class 12 (busses) is no longer allocated to any two-axle vehicle.

Table 4 shows the performance of the algorithm on the training set. On this set the algorithm incorrectly classifies 139 vehicles, which corresponds to 16.5%. On the verification dataset these figures are 150 and 17.8% respectively.

Table 4 - Training set, 16.5% classified incorrectly

	WIM-NL													
TRUE	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
1	72	1			14		6						1	94
2		193												193
3			29									3		32
4				12				1					5	18
5					24			1				1	29	55
6						10				14			2	26
7					1		52						1	54
8					16			113					1	130
9									169				7	176
10										2				2
11											15		4	19
12		24	7											31
13													13	13
Total	72	218	36	12	55	10	58	115	169	16	15	4	63	843

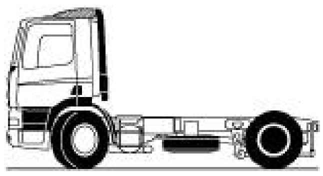
4. CQM Approach

Using standard statistical techniques to classify vehicles did not yield very intuitive results. An intermediate station was developed that does not exist in standard statistical classification theory. The vector **U** is transformed into an *interpretable* one-dimensional string *S*. A string *S* can be drawn based on the length of the vehicle and the distances between axles. As an example assume that the string **U** = (700,50,200,50) meaning that the length of the truck L=700cm, the distances between two successive axles are 50, 200 and 50 respectively. Figure 4 shows the transformation of this data.

U = (700,50,200,50) ⇔ “-0-0----0-0--

Figure 4 - Transforming Data into a String

Each character in the vehicle signature string represents a length of 50 cm. Given this method of representing a vehicle with a string, the truck in Figure 5 can best be represented by string 1. In practice however it will be impossible to come to this string since it would require data on the overhang at the front of the vehicle. Data which cannot be retrieved from the roadside system at this time. A choice was made to start each string representing a vehicle with a single dash, followed by the first axle, the following dashes and O's representing the axles are given by the axle separation information. If the total length of this string corresponds to a total vehicle length less than the measured value, dashes are added to make up for this difference. Any overhang at the front of the vehicle would thus be added to the overhang at the back in the string representation. In the case of the example shown in Figure 5, this would result in the second string.



1) --O-----O-

2) -O-----O--

Figure 5 - Conversion of Vehicle to String

4.1 Base strings

This string representing a passing vehicle can be compared with a set of base strings; one or more for each base class (with axle count indication) that is taken into account. The distance between the measured string and each base string can be calculated. The vehicle will be assigned to the base class for which the distance between measured string and base string is the smallest. The training set was used to define a base string for each of these classes. A subset of these base strings is shown in the second column of Table 5.

4.2 Distance between two strings

Given a set number of operators, such as inserting a character, removing a character and transposing two characters, a string can be turned into any other string. The string representation of a passing vehicle can thus be transformed to any of the base strings. Counting the number of edit steps required for each transformation gives the distance between two strings. This distance allows to identify the base string and corresponding vehicle class which best matches the passing vehicle.

Since the letter 'O' refers to an axle, it does not make sense to add or remove this character, this operation is therefore not permitted when transforming the vehicle string to any of the base strings. As a result only those base strings are considered that represent a vehicle class with the same number of axles as the passing vehicle.

Converting one string into another using the operators described above, can be done in many different ways. The objective however, is to use the minimal number of permitted edit steps so that a fair comparison can be made between the different base strings. To achieve this, a standard cost component, or penalty, is introduced and is associated with each edit step. The goal is thus to transform the signature string to each of the base strings incurring minimal costs. A Dynamic Programming algorithm is used in this process.

4.3 Refinement

On the Dutch highways there is no such thing as a standard truck, bus, or tractor/semi-trailer. Dimensions differ to some degree from vehicle to vehicle of the same class. There is a wide variation of trailers, whereas the trucks are relatively uniform. When matching a vehicle signature string to one of the base strings it therefore makes sense to make it relatively ‘cheap’ to shorten a semi-trailer in order to achieve a match, and make it ‘expensive’ to alter the length of the truck.

For this purpose the characters ‘~’ and ‘*’ are introduced into the base string. In addition we allowed the edit costs components to be variable. When comparing the vehicle strings to each of the base strings these characters can both be read as ‘-’. Only when one of these characters needs to be removed or inserted to achieve a match will there be a difference. Inserting or removing the character ‘*’ is the most expensive, since this corresponds to altering the length of a truck; the character ‘-’ can be removed or inserted against standard costs, ‘~’ is used in the semi-trailer section of the base string and can be considered cheap to remove or insert.

4.4 Future Refinement

There are no restrictions to the characters that can be used in this matching process. If additional information were available from the roadside system, this information could be integrated into the string as a different character. An example would be the detection of a lifted axle indicated by ‘X’. A vehicle which would currently generate signature 1 could in theory be matched to either a V_2 or a B_2. If however the following signature 2 was observed we could determine that the vehicle could not be a bus since we could only map it to the base string defined below. The vehicle would be classified with subclass V_{11}.

Signature 1: -0--------0----
Signature 2: -0--------0-X–
New base string (V2): -0--------0X-

Table 5 - Base strings

Vehicle class	Base string	Refined base string
V_2	-0--------0-	-0--------0-
V_3	-0-0------0-	-0-0------0-
V_3	-0-------00-	-0-------00-
V_4	-0-0-----00-	-0-0-----00-
V_4	-0---0-0-0--	-0---0-0-0--
V_2A_2	-0--------0--------0--------0-	-0********0--------0--------0-
V_2A_3	-0--------0-------0--------00-	-0********0-------0--------00-
V_3A_3	-0-------00-------0------00-	-0*******00-------0------00-
T_2O_1	-0-----0-------------0----	-0*****0-------~~~~~~0--~~
T_3O_3	-0---00------------000--	-0***00------~~~~~~000-~
B_2	-0--------0-------------	-0--------0************-
B_3	-0----------00-----------	-0----------00**********-

4.5 Post Processing Step 1

It is possible that a vehicle which is to be classified is not in fact a bus or a truck but a van or a car, with or without a trailer. Any vehicle below 3500 kg is assigned class *car,* any vehicle with three or more axles which weighs less than 7000 kg is also categorised as *car,* since these vehicles generally correspond to vans or cars with trailers. In addition each class is assigned a minimum weight, if this minimum weight is not met for a particular class, this class will be ruled out and only the remaining classes will be considered for a match. The minimum weight of a tractor/semi-trailer is of course higher than that of a regular two-axle truck

Table 6 - Minimal weights

Base Class	**Weight**
V_2	3,500
V_3	7,000
V_4	7,000
V_2A_2	7,000
V_2A_3	7,000
V_3A_3	7,000
T_2O_1	10,000
T_3O_3	10,000
B_2	3,500
B_3	7,000

4.6 Post Processing Step 2

The new algorithm assigns a base class with axle count information to each passing vehicle. However, to be able to determine the maximum load for a particular axle, the subclass, as described in section 3.1, is required for each vehicle. A simple post processing step can be applied to obtain the subclass from the assigned base class. The procedure will return to the original axle separation data and check it against the law. It will look at axle one and two, if the separation is less than the maximum prescribed by law for it to be considered a pair, the two will be said to be a pair etc. This procedure will be done for both the truck and the trailer.

4.7 Example

Passing Vehicle:

Axle count:	3	; Axle separation:	578 cm, 182 cm,
Total length:	878 cm,	; Weight:	8970 kg

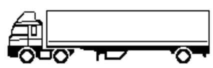
Step 1:
Derive signature string based on the above vehicle characteristics, as described in section 4.

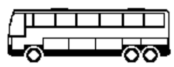
`-0----------0--0-`

Step 2:
Determine classes that have equal axle count:

1. V_3 `-0-------00-`


2. V_2A_1 `-0--------0-------------0----`


3. T_2O_1 `-0-----0-------------0----`


4. B_3 `-0----------00----------`


Step 3:

Determine *cost* of converting the vehicle signature string to the base string for each of the classes that are being considered: These costs are 10, 30, 20, 28 for options one through four respectively.

Step 4:

Check minimum weight restriction for each of the classes being considered and select the best possible match from the remaining options: Minimum weight is 7,000 kg for V_3, V_2A_1 and B_3, and 10,000 kg for T_2O_1. The latter is therefore excluded as a possible match. The best match is therefore option 1: V_3, since this option has minimal cost.

Step 5:

Determine the subclass based on the assigned base class and the axle separation data: All axle separations exceed 180 cm (Dutch legal limit); they can thus all be seen as single axles. The subclass is therefore V_{111}.

4.8 Calibration

The construction of the base string can be viewed as a calibration of the algorithm. The strings listed in Table 5 were created based on a Dutch dataset. It is likely that for this approach to be used in other countries, with possibly different vehicle configurations, a re-calibration is called for. Re-calibration would also be required if new vehicle types are introduced. These calibration issues would apply to all classification methods.

4.9 Results

Tables 7 and 8 show the performance of the new algorithm. The training set was used to construct the algorithm and could thus be viewed as biased.

Table 7 - Training set, 1.8% classified incorrectly

	DWW													
TRUE	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
1	93											1		94
2		188										5		193
3			32											32
4				18										18
5					51			3	1					55
6						26								26
7			2				52							54
8				1				129						130
9									176					176
10										2				2
11											19			19
12		1	1									29		31
13													13	13
Total	93	189	35	19	51	26	52	132	177	2	19	35	13	843

Table 8 - Verification set, 2.4% classified incorrectly

	DWW													
TRUE	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
1	94													94
2	1	206										3		210
3			25									1	1	27
4				12										12
5					61			1	4					66
6						37								37
7			1				48							49
8				3				99						102
9									186					186
10										1				1
11											11			11
12		4			1							35		40
13													7	7
Total	95	210	26	15	62	37	48	100	190	1	11	39	8	842

No automatic tuning of the algorithm has been done, it was therefore not expected that the algorithm would perform significantly worse on any other dataset. This expectation was reinforced by the results on the verification set. The new DWW algorithm classified 15 vehicles of the training set incorrectly, which corresponds to 1.8%. The verification set resulted in 20 incorrectly classified vehicles, corresponding to 2.4%. Combining the results achieved with the existing algorithm and those yielded by the new approach are given in Table 9. The results achieved through correcting the existing algorithms to better recognise cars and vans are listed as *modified* in the same table.

Table 9 - Results summary

	Training set	**Verification set**	**Average**
Euro13	29.7%	32.0%	30.9%
Modified Euro13	21.6%	23.8%	22.7%
WIM-NL	16.5%	17.8%	17.2%
Modified WIM-NL	14.0%	15.7%	14.9%
DWW	1.8%	2.4%	2.1%

In addition to the significantly better results yielded by the new algorithm, the DWW algorithm is also extremely flexible. It is easy to add additional vehicle classes if new vehicle configurations are taken into use at some time in the future.

5. Results from the field

Since the development of the new DWW algorithm described in the section above, it has been implemented, integrated in the roadside system, and deployed at all Dutch Weigh-in-Motion sites. After the initial deployment some additional base strings were added to the set shown in

Table 5 to account for vehicle configuration that either did not exist at the time of development, or configurations that were not present in our dataset.

Since the deployment in February 2004 and the fine-tuning that has been done since then the performance of the new algorithm has been as expected, with only 2 -3 % of vehicles being classified incorrectly.

Both the existing *WIM-NL* classification method and the new DWW method were run side-by-side for some time. Since the new method derives the subclass from the base class (with axle count) automatically, classes were detected that were not previously part of the *WIM-NL* set. Adding these classes to this set improved the performance of the old method; which only shows that the new method is more robust for small changes in vehicle types.

6. Conclusions

The algorithms currently available have been shown to be inaccurate when used to classify vehicles passing the WIM locations. These algorithms could in theory be tuned to improve their performance on the dataset provided. Making minor changes to the existing algorithm has resulted in a performance improvement of the live system. However, these changes do not change its sensitivity to measurement error, and small changes in vehicle types.

The new DWW algorithm is an innovative approach that has proved to be very effective when used to classify vehicles. The error percentage is significantly lower than that of the alternative methods. The method is flexible, in that it is easy to add or change any of the classes. When adding a new class however, care should be taken to ensure that classifications that were previously correct are not affected in any way. The datasets used in this project could be used for such purpose. The method can be easily adapted to take into account additional information that may be draw from future roadside systems, such as the overhang at the front of a vehicle, raised axles etc.

As is the case for all classification methods, it is recommended to calibrate this new algorithm for each country, since the vehicles that are used may differ from those in regular use in The Netherlands. A periodic re-calibration is also recommended to accommodate for new vehicle types, and changed configurations.

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ADVANCED SYSTEM SOLUTIONS FOR NEW WIM APPLICATIONS

  

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Abstract

This paper presents actual and novel application areas of WIM systems for basic research, ITS and remote overload enforcement. As examples, three recent systems are described to illustrate the versatile data processing and system layout possibilities: (i) a recently started long-term test project organized by the South Korean Highway Corporation, (ii) a new approach for city traffic control and road protection currently tested in Prague, and (iii) a further multi-purpose WIM application with an example from the Swiss alpine region. WIM based traffic flow analyses are useful beyond statistics and traffic planning, for prognostics and automatic influencing the rolling traffic. The evaluated results can also be used as a base for determining dimensions in road and bridge constructions or for optimizing resurfacing work.

Keywords: Weigh in Motion, Overload Enforcement, Pavement Research.

Résumé

Cet article présente les domaines d' application actuels et nouveaux de systèmes de pesage en marche pour la recherche, pour les systèmes de trafic intelligents (ITS) et pour le contrôle des surcharges à distance. Trois exemples sont donnés pour illustrer les diverses possibilités de traitement des donnés et d' architectures des systèmes : (i) un projet d'essai à long terme lancé récemment en Corée du Sud par la South Korean Highway Corporation, (ii) un nouveau concept de contrôle du trafic et de protection des routes testé actuellement à Prague, et (iii) une application des systèmes de pesage en marche pour les tunnels autoroutiers transalpins en Suisse. Les données de pesage en marche sont utiles à des fins statistiques et de contrôle du trafic, pour les prévisions sur les itinéraires empruntés par les poids lourds, pour le dimensionnement des chaussées et des ponts, ainsi que pour l' optimisation des périodes de maintenance.

Mots-clés: Pesage en Marche, Contrôle des Surcharges, Recherche sur les Chaussées.

新動態地磅應用之先進系統解決辦法

摘要：

本篇報告指出動態地磅 (Weigh-in-Motion, WIM) 系統於基礎研究、ITS 及遠端超載執法上之現況及新穎之應用情形。文中舉出三個系統之案例，以說明多方面的資料分析及系統安排之可能性。1. 由南韓公路局進行之長期測試計畫、2.　近期在布拉格測試之一項都市交通控制及鋪面保護的新方法、以及 3.以瑞士阿爾卑斯山區爲例之多目標動態地磅應用。以動態地磅資料爲基礎之車流分析除了可進行資料統計及交通規劃之外，亦可對交通產生影響。其評估結果可作爲決定道路幾何設計及橋樑建造之基礎，抑或可作爲鋪面大型養護最佳化之依據。

關鍵字：動態地磅、超載執法、鋪面研究

1. Introduction

Weigh In Motion (WIM) systems are employed at an increasing rate throughout the world for coping with the dramatically rising costs for maintaining the traffic infrastructure.

Accurate vehicle load data are vital for ensuring that a nation's highway system remains intact and safe. Continuous overload detection is an important means for restraining illegally operating carriers, often more efficient than punctual enforcement actions. In view of traffic engineering WIM data are useful to improve heavy traffic efficiency by weight-dependent speed or detour route selection, as well as for preservation of limited weight bridges and roads. Furthermore, WIM data can be used to predict future traffic volumes for planning and new constructions, for the management of maintenance activities, as well as to identify locations or carriers with frequent overloading problems.

In this paper three examples for novel application areas of WIM systems for basic research, ITS (Intelligent Traffic Systems) and remote overload enforcement are described to illustrate the versatile opportunities of data processing and system architecture.

WIM based traffic flow analyses are useful beyond statistics and traffic planning, for prognostics and automatic influencing the rolling traffic.

2. South Korea Long Term Test Project

A recently started long-term test project for basic research has been organized by the South Korean Highway Corporation. The research topics comprise as specific areas pavement, structure and geotechnical performance evaluation. The experimental area is equipped among several measuring systems also with a multilane WIM system.

The experimental track is located on the Jungbu Inland Expressway Yooju-Chungju in the south-western region of South Korea. The construction period of the experimental track was from April 1997 to December 2002.

2.1 Site Geometric Design (Figure 1) and Aims

The main objectives of this project are as follows:

- Reduction of the construction and maintenance costs for highway system
- Development of a “Korean Pavement Design Guide and Specification”
- Development of models for long-term highway pavement performance evaluation
- Assessment of structural systems for highway infrastructure
- Highway traffic safety improvements

The research topics can be in detail divided into three specific areas:

Pavement

- Performance evaluation of continuously reinforced concrete pavement
- Development of water proofing system specifications for bridge deck pavement

- Quality assurance program for pavement constructions
- Automation and optimisation of pavement management systems (PMS)
- Forecasting system for the optimisation of winter maintenance in view of pavement freezing

Structure Performance Evaluation for

- high strength pre-stressed concrete beam bridges
- composite box girder bridge with inclined web and open top
- retaining walls with geosynthetic reinforcement

Geotechnical

- Selection of back fill materials for geotechnical structures
- Retaining walls with geosynthetic reinforcement

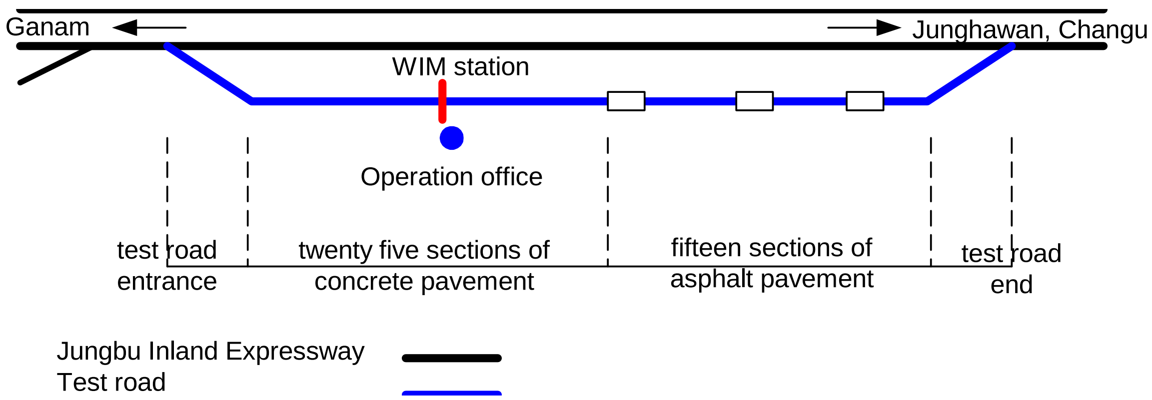

Figure 1 - Experimental Track Sections

2.2 Site and Pavement Condition

The total length of the test road is 7'700 m and the road itself has two traffic lanes in one direction. The experimental track is divided in fifteen asphalt composite and twenty five concrete pavement sections. All layers of the road construction are equipped with strain gages, thermocouples, time-domain reflectometry probe and pressure sensors to measure the behaviour of different road materials under real environmental conditions.

The Korean test site also includes three test bridges and three different geotechnical structures. Figure 3 shows an overview from the operation office over the main parts of the test road. During the test periods the pavement behaviour in the different sections, (Figure 2) will be measured under the actual traffic loads and environmental conditions, to investigate pavement damages and to optimize pavement design guidelines.

For comparing the measurement data on the structural response of the bridges it is necessary to establish in real time the dynamic loading imposed by the passing of the vehicle axles. To measure the dynamic influences on the behaviour of the road construction layers, the Korean Highway Corporation ordered a special high speed WIM system developed by Kistler Instrumente (Switzerland) and Infitron Inc., a Korean company.

The HS-WIM system uses quartz crystal sensors which are available in lengths of 0.75m and 1m and thus can be combined easily to cover the full width of a traffic lane in steps of 0.25m. On the Korean experimental truck the sensors are installed in two parallel rows per lane.

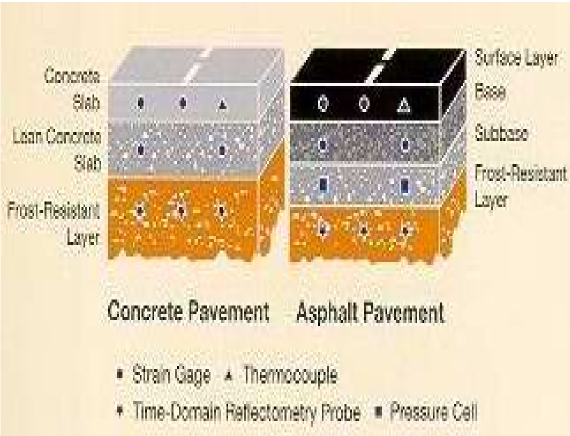

Figure 2 - Road Designs

Figure 3 - Test Track Overview, Operation Office

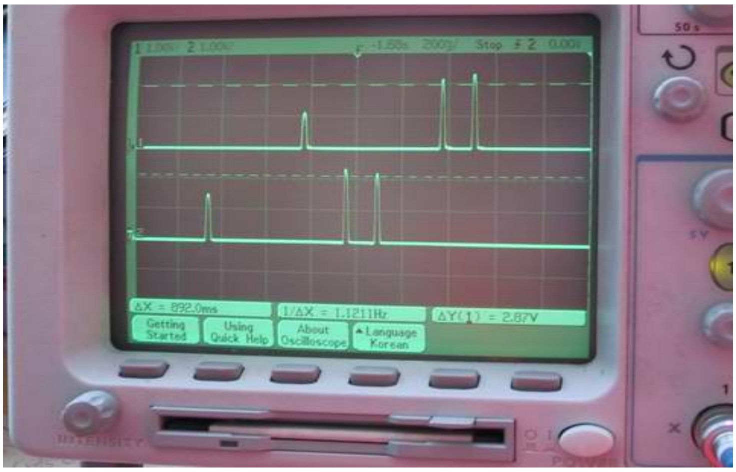

Figure 4 - Typical Signal Shapes with Quartz Sensors

Figure 5 shows the deviation of the dynamic gross vehicle weights (GWVs), compared to static weights on the 1 lane, for 37 overpasses with a 3-axle unloaded reference vehicle during the calibration procedure. The control measurements consisted of 35 runs per lane using two different trucks (2 axles and 3 axles), the speed varying between 10 km/h and 80 km/h. The results shown in Figure 5 guaranteed a good base for the following measurement periods.

Figure 5 - Measurement Example 3-axle Truck

The HS-WIM system uses quartz crystal sensors which are available in lengths of 0.75m and 1m and thus can be combined easily to cover the full width of a traffic lane in steps of 0.25m. On the Korean experimental truck the sensors are installed in two parallel rows per lane.

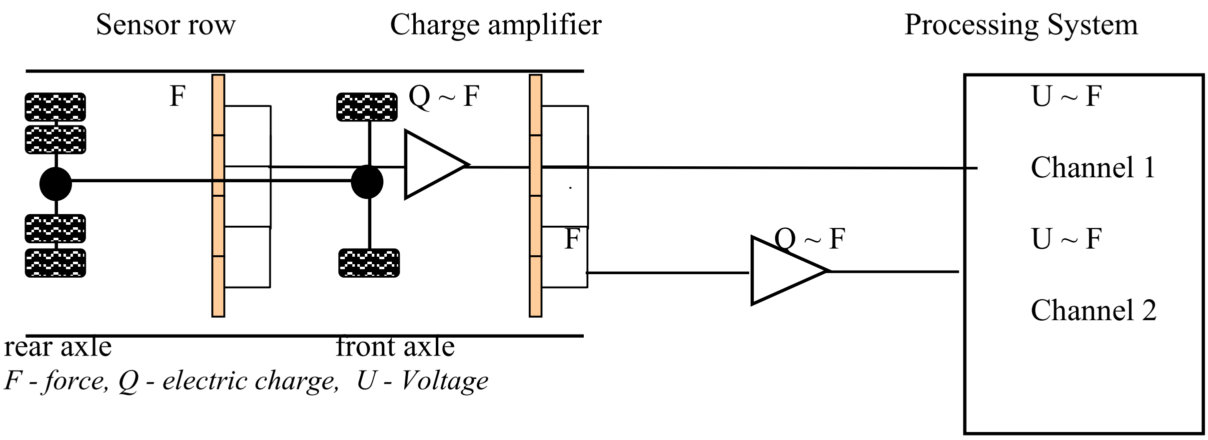

Figure 6 - Measuring Chain

2.3 Universal Signal Processing for Low as well as for High Speeds

Conventional WIM systems generally have some shortcomings especially in the low speed range (<1km/h - 20km/h). Basically the problems of commercial electronic equipment can be assigned to the following areas:

- Speed measurement: - accurate speed measurement is necessary for signal processing. Over In the case of very slow traffic (traffic jam, city area etc.), the speed can vary considerably over the distance between the two sensor rows. The vehicle deceleration or acceleration over the sensors can cause considerable deviations especially for low speed WIM measurements.

- The time constant of the charge amplifier must be adapted according to the speed range (<1km/h - 200km/h). Conventional charge amplifiers provide short time constants to avoid charge drift effects which could cause saturation or overload and therefore are limited generally to velocities above 10 km/h.

For the signal analysis of quartz sensors a special algorithm was adopted to realise an accurate weight determination over a wide range of velocities and tire characteristics. Quartz sensors are strip-shaped with an active width of 53 mm, thus covering only a fraction of the tire footprint (latch) length which can vary typically from 100 to 300 mm according to tire dimension, load and inflation pressure. Thus in contrast to weigh plates the wheel load cannot be determined by measuring the peak force. For taking into account the wheel force shunted to the pavement before and after the tire contact zone on the sensor, it is necessary to consider the line integral of the wheel force acting on the sensor, from the first contact (touch-on) until the lift-off of the wheel. As the latch length is not a directly measured variable it is determined from the sensor contact time ***t*** by multiplying with the velocity ***v***:

$$F = v * \int_{t1}^{t2} [Q(t) * d(t)] \qquad \text{[kN]} \tag{1}$$

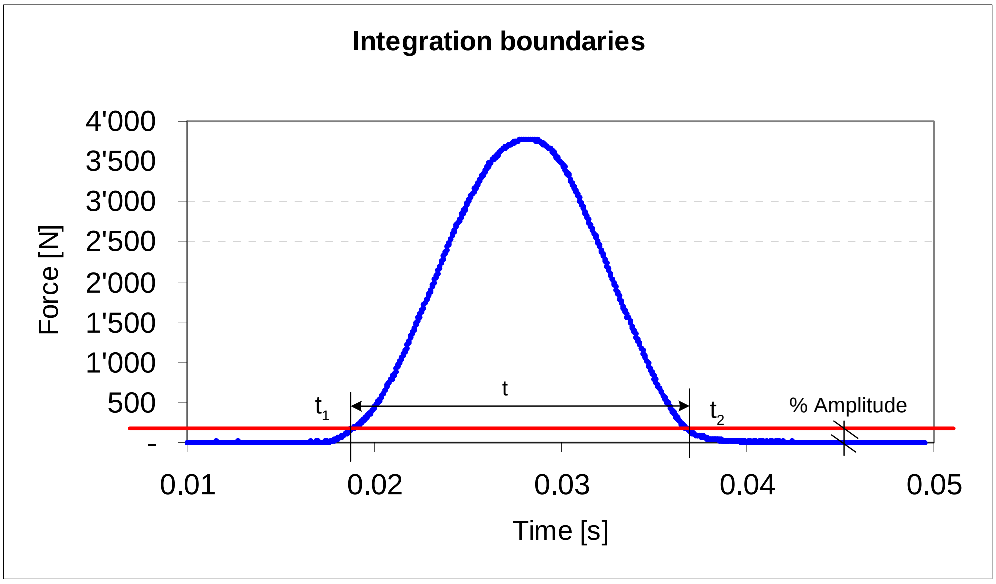

Figure 7 - Signal Processing

Thus although according to the inflation pressure the peak force increases and the latch length decreases, the area under the force-time curve remains constant for a given velocity and is proportional to the wheel load. The inflation pressure influence on the signal shape is specially significant *(more pronounced)* with lightweight vehicles, as shown in Figure 8

The velocity is measured by the passage time from the first to the second sensor row. As the velocity is a proportional factor in the load determination, its accuracy is directly influencing the WIM results. This means that the two sensor rows have to be installed exactly parallel and orthogonally to the driving direction. The spacing between the two sensor rows is selected according to the average speed distributions. On highways typically 4 metres with a parallelism of < 4 mm is ideal to keep velocity errors below other dynamic weight errors. For an accurate measurement also the clearcut signal shape of quartz sensors is essential to define the velocity timebase as well as the integration boundaries.

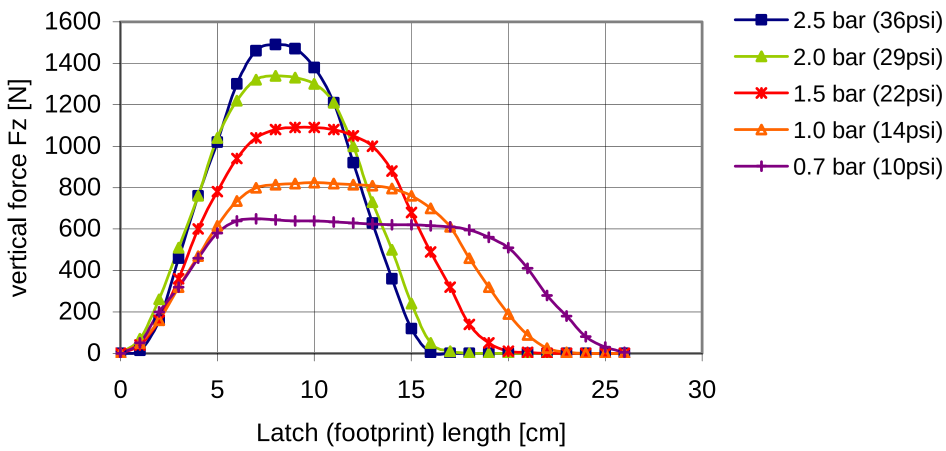

Figure 8 - Examples of Signal Shapes for Varying Tire Pressure

The latch length is a calculated factor useful for estimating the tire type and tire pressure.

$$Latch \cdot length = 100 * \left[\left(\frac{v}{3.6} \right) * \left(\frac{t}{1000} \right) - 0.053 \right] \qquad \text{[cm]} \qquad (2)$$

The piezoelectric quartz sensors generate electric charges with a sensitivity of typically 1.8 nC/kN. Charge output moreover enables easy summation of the forces on several sensors by simple parallel connection, e.g. to add left and right wheel loads to obtain axle loads. The charges are amplified and converted into proportional analog voltages in the range of 0 < 5 V. The summed output voltages pass an anti-aliasing filter with a 600 Hz cut off low-pass and are digitized with a 12 bit resolution ADC with a sampling rate of 2 kHz.

To enable resolution of broadened force impulses of slow vehicles the charge amplifiers used in the described systems however have long time constants in the order of 100 seconds.

For achieving long time constants without baseline drift problems, low temperature sensitivity and high insulation resistance sensors must be used.

3. City WIM

This universal signal processing procedure is further applied in a new approach for city traffic control and road protection which shall be presented by the example of the "City WIM system" currently tested in Prague, Czech Republic. Its main application aims are the prevention of overloading and damaging the inner urban arterial by heavy traffic and improving the transit traffic.

WIM systems enable versatile applications also in urban areas:

- Traffic engineering
- The three traffic flow parameters of the "Equations of Continuity", namely the traffic volume V [vehicles/hour], velocity v [km/h], traffic density D [vehicles/km/lane] have to be estimated by a standard WIM measurement. Additionally to the mentioned parameters of the standard WIM station, an extended vehicle classification, axle loads and gross vehicle weight data are obtained.
- On-line traffic control with the detailed traffic stream analysis.
- Traffic stream data with calculated peaks with variable time intervals (5, 10, 15, 20, 30, 60 minutes) is displayed on the traffic operator's screen or directly fed into the on-line traffic control software in order to influence variable traffic signals.
- Preventive weight screening checks with license plate recognition
- The database of the overloaded vehicles with the weight data and license plate recognition can be assigned to the vehicle owner register. Carriers with frequently overloaded vehicles or axles can be detected and informed by police or road authority.
- Enforcement - the screened vehicles pre-selected as overloaded are re-checked on a static scale specified according to OIML standards and can be penalized.

As main features of City WIM systems, the following functions can be mentioned:

- Urban and rural areas are very sensitive to environment impacts like noise, vibration and exhaust emission in view of the level of life quality.
- Efficient traffic control is of utmost importance in the city area and agglomeration, as congestion are a daily phenomenon. To reduce this negative aspect, on-line traffic data collection with the aims of traffic dosing to achieve an optimal distribution of traffic streams on the arterial roads and to split the traffic volume proportionately on the whole road network.

Figure 9 - Layout South Connection

Figure 10 - Electronics

The realization of a pilot project in the Czech Republic is described below. The installation of the Prague City WIM system started in 2004 with an installation on the six-lane "South connection" urban arterial road. It canalizes the heavy traffic into the first traffic lane, so that all heavy vehicles must pass the WIM sensors. The standard high speed WIM system had to be optimized to perform over an extended speed range from 1 km/h to the 200 km/h speed limit. The system optimization includes adaptations of the signal amplification and improved signal processing in order to achieve a combination between the low speed and high speed WIM systems. This is a prerequisite for the adaptation to the special traffic conditions in urban areas.

GVW	Vehicles
< 38 t	1 447
> 38 t	476
Total	***1 923***

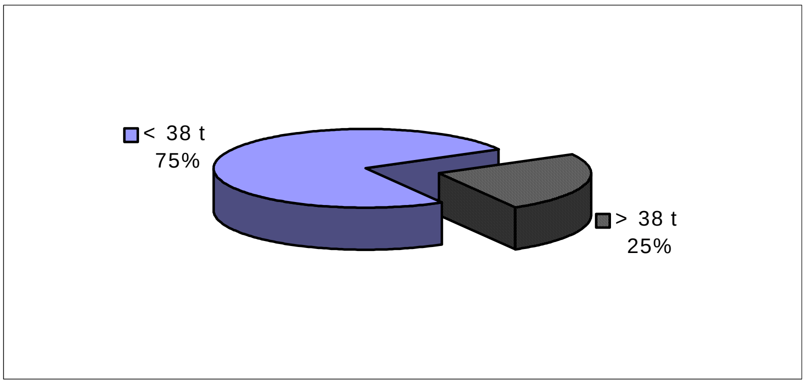

Figure 11 - Overloaded Vehicles on South Connection Lane 1/24 Hours

4. Remote and Virtual WIM

A further multi-purpose WIM application comprises the online traffic data evaluation operated in various control modes. An example from the Swiss alpine region illustrates specific methods of remote overload detection in severely intersected terrain with long tunnels.

Remote WIM sites generally comprise multilane sensor and video systems with online signal transmission to a distant control centre. The principle of a virtual WIM system is similar to that of a remote WIM site uses existing or new traffic data collection sites by integrating them into a network. For each vehicle the traffic data are collected, including vehicle classification and weight data and then transmitted together with a video picture, to an enforcement operator. In case of an overloaded vehicle, the relevant weight data are highlighted on the screen together with the picture of the vehicle. The vehicle may be pulled over for further checking. The pre-selection of vehicles allows enforcement personnel to concentrate on the potentially overloaded trucks, instead of detaining many unsuspicious vehicles from the traffic stream. A typical virtual WIM system complements fixedly installed automatic high speed WIM stations and remote data evaluation, traffic control and static scale systems.

The different data formats and retrieving modes can be selected for the whole WIM station or for individual traffic lanes according to the user requirements. The multi-user system is based on a password access control system defined separately for every WIM station.

The following example from the Swiss WIM network shall illustrate this. On the highway A2 (main North-South transit road through the Alps region from Germany to Italy), a five-lane remote traffic WIM system was installed in the Monte Ceneri tunnel. The heavy traffic flow control is performed with use of the high speed WIM equipment: Within the tunnel, the WIM sensors, video and height control systems are installed for monitoring the overloaded or excessive height trucks (see Figure 12). In addition, a warning signal can be passed on to the highway police central station.

4.1 System Characteristics

The "Monte Ceneri Tunnel" consists of two tunnel tubes with two (Northbound) and three (Southbound) lanes per tube, all equipped with the traffic control system. The operational principle of the traffic control system can be described as follows:

- The WIM traffic data system consists of 32 quartz crystal based WIM sensors (Lineas) on 4 lanes, data retriever including data transmission, software, and processor power supply
- Induction loops triggering infrared detectors for the height control system, in the South – North direction
- Video cameras including installation for permanent registration of traffic flow
- Traffic signals, partly variable for adaptive control
- Local control facilities

Improvements of traffic flows can be achieved among other means through harmonization of speeds on the individual traffic lanes of the motorway by:

- Warning of overloaded vehicles, etc.
- Warning of traffic congestion
- Traffic-adapted speed signals
- Avoidance of traffic obstructions

4.2 Data Acquisition and Transmission

Traffic-flow data (speeds, traffic volumes) are acquired locally in the electronics installed in roadside stations, including the individual axle loads and the GVW of the vehicles, the distances between vehicles, traffic statistics per vehicle classes, speed and time intervals.

The online data from the heavy traffic and the video sequences of infringing vehicles are transferred to the traffic control center. The combined police and road administration center is situated near to the control and measuring facility, some 3 km downstream in northbound direction.

All "vehicle by vehicle" measurement data are additionally transferred to the ASTRA (Swiss federal roads authority) center for the subsequent statistic evaluation and data archiving.

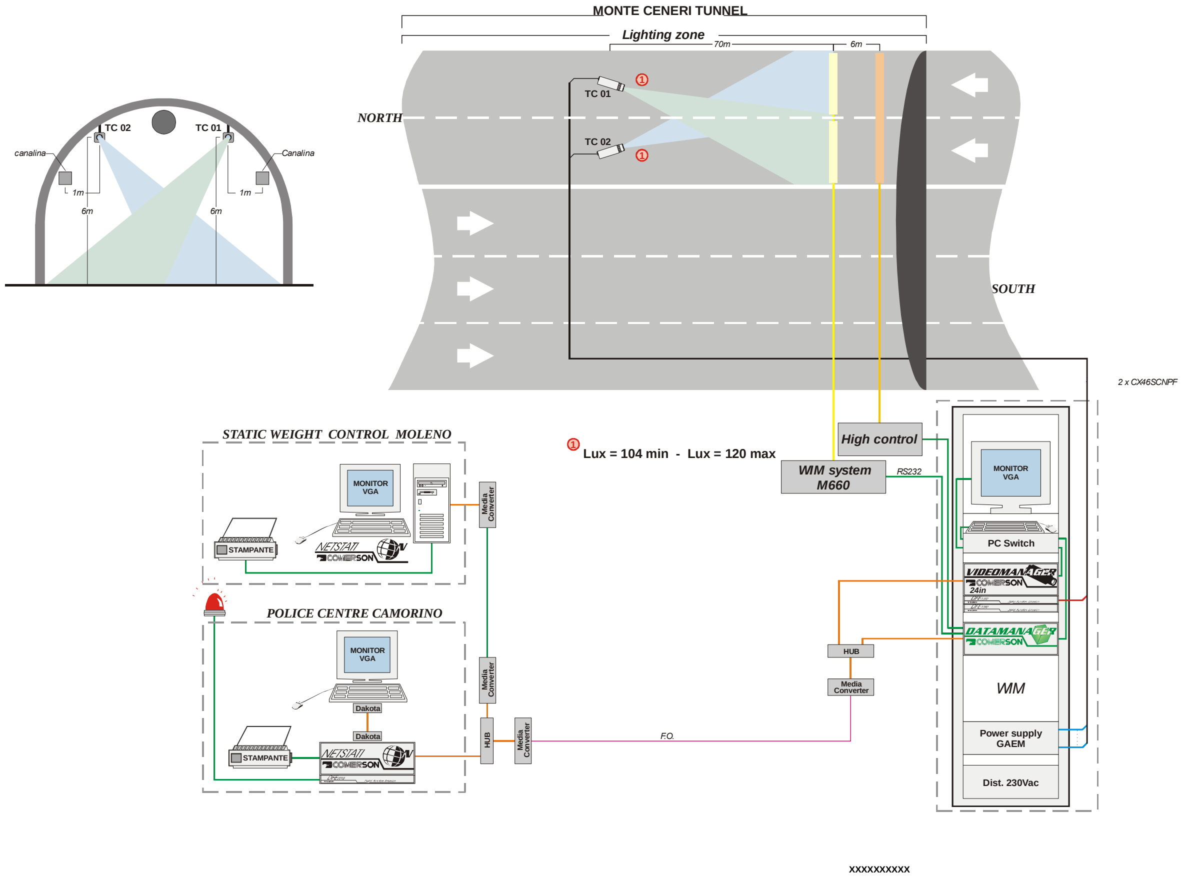

Figure 12 - Remote WIM System Overview - Tunnel Control Center and Static Weighing

4.3 Data Analysis

The traffic control center analyses the results of the measurements and the video sequences collected by the WIM site, to enable an individual pre-selection of overloaded or excessive height vehicles. These data are simultaneously transferred to the next police control station downstream, equipped with a low speed weighing system certified for enforcement.

Gross offenders will be automatically recorded and identified in real time. They will be diverted to the scale for mandatory static weighing and enforcement.

The data of these vehicles are recorded in a separate database for police.

Thus with the remote WIM system this pre-selection can be achieved without the unpopular slowing down of the overall traffic flow, because only the pre-selected vehicles will be stopped and weighed statically.

4.4 Individually Variable Traffic Data Format

The WIM station can be monitored and its data collected hourly, daily or weekly according to operational requirements. The remote mode can be set as read-only (RO) for example for the police or local road administration office use, or as read-write (RW) access for the system integrator. The potential for data corruption trough hacking is thus reduced. The system has three levels of access:

- Master user can setup all the systems parameters such as modem details, transfer protocols, location of data folders. He only can set times and dates for status and retrieval pool commands etc. All parameters can be set and activated when required.
- Expert user will only see a reduced set of options
- Normal user has read-only access

Every WIM site is individually configurable for modem details, unit type, PC COMM port, baud rate, read only and read/write passwords, filename and sensor configurations.

The telemetry software and data retrieval system supervises an outstation database containing the phone number, site details and so on. Once a system is set up, it runs autonomously and generally does not need any operator intervention.

5. Summary

The three examples for novel application areas of WIM systems include basic pavement and infrastructure research, ITS and remote overload enforcement.

The mentioned WIM applications are very demanding in view of accuracy and long-term stability under harsh environmental conditions, as well as of installation constraints.

The described universal signal processing method allows for low as well as for high speed WIM measurements with the same sensor and electronic components.

With a minor software modification, special requirements for urban area, tollgate and border applications can be fulfilled with the same hardware as currently used for the standard highway and minor road WIM systems.

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VALIDATION OF A WIM SMOOTHNESS INDEX DERIVED FROM PROFILES COLLECTED BY INERTIAL PROFILERS



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Abstract

The smoothness of the pavement at the location of a weigh-in-motion (WIM) scale has been shown to affect the accuracy and operation of the equipment. To evaluate pavement smoothness at WIM locations without lane closures the LTPP program has developed a method using profiles collected by inertial profilers. The smoothness index calculated from the data is compared against a set of threshold valued that identify three domains: not expected to impact calibration, may affect calibration and calibration is not expected to be possible. A field validation using both tractor-trailer combinations and straight trucks has determined that the middle domain has reasonable bounds but has been unable to find extremely smooth or extremely rough pavements at WIM installations to definitively test the bounds.

Keywords: WIM, Weigh in Motion, Pavement Smoothness.

Résumé

L'uni de la chaussée au droit d'un site équipé d'un système de pesage en marche (WIM) influence la précision et la mise en œuvre de l'équipement. Pour évaluer l'uni de la chaussée sur les sites de pesage en marche sans fermeture de voies, le programme LTPP – Evaluation du comportement à long terme des chaussées - a développé un procédé de mesure de profil inertiel. On compare l'indice d'uni calculé à l'aide des données avec un ensemble de valeurs seuils qui définit trois domaines: sans effet sur l'étalonnage du système, effet possible sur l'étalonnage, et étalonnage pratiquement impossible. Une vérification par l'essai sur site avec des camions avec et sans remorques, a déterminé que le domaine intermédiaire a des limites raisonnables, mais nous n'avons pas pu trouver de sites de pesage en marche à chaussée parfaitement lisse ou très rugueuse pour valider les limites extrêmes.

Mots-clés: Pesage en Marche, Uni de Chaussée.

以慣性式平坦儀收集之道路剖面資料推算之動態地磅平坦度指標之驗證

摘要：

動態地磅 (Weigh-in-Motion, WIM) 的精度與運作受設置處之鋪面平坦度影響。為了在不封閉車道的情況下評估動態地磅所在位置之鋪面平坦度，長期鋪面服務績效研究 (Long Term Pavement Performance, LTPP) 計畫以慣性平坦儀進行道路剖面資料之蒐集。將由道路剖面資料所計算而得之平坦度指標與門檻值比較後，可將平坦度對動態地磅的影響分為三種不同輕重程度：分別為不預計會影響校估、可能影響校估、以及無法進行校估等三種。使用全聯結車 (tracker-trailer) 以及大貨車 (straight truck) 現場驗證結果發現，「可能影響校估」之平坦度區間具有合理的上下限值，但無法找到極端平坦或極端不平之鋪面針對其他兩區間臨界值進行探討。

關鍵字：動態地磅、鋪面平坦度

1. Background

Accurate loading data are vital to the success of the Long-Term Pavement Performance (LTPP) program. Loading data within the LTPP program are collected with WIM scales. The dynamic motion of the trucks affects the accuracy of the data collected by the scales. In turn, the dynamic motion of the trucks is affected by the pavement roughness prior to and immediately after the WIM scale. Short wavelength roughness affects axle motion, while long wavelength roughness affects body motion. The question facing the LTPP program that initiated this work was - "How rough is too rough to obtain accurate measurements of the truck loads?"

The primary tool used within the LTPP program to measure pavement roughness is high-speed inertial profilers (LTPP TSSC, 2004a). The profilers are equipped with laser sensors to collect elevation data at 25-mm intervals along three paths, typically the wheel paths and the center of the lane. The use of profilers reduces the need for lane closures and permits profiling extended sections of roadway to find optimal locations for WIM equipment based on pavement smoothness.

To evaluate pavement smoothness the intent was to find an index based on profiler data that could predict the ability of a site to produce what LTPP considered research quality data. WIM data for LTPP is research quality when the 95 percent confidence interval of the mean errors for loading characteristics falls within the bounds shown in Table 1 below (LTPP TSSC, 2001). The bounds for the limits were based on the tolerances for 95 percent probability of conformity for Type I WIM systems as described in ASTM E-1318 (ASTM, 2004). LTPP omitted the wheel load criterion associated with Type I equipment.

Table 1 - LTPP Bounds for research quality WIM data

Loading Characteristic	Allowable Limits on Errors
Single axles	$\pm$20 percent
Tandem axles (and other axle groups)	$\pm$15 percent
Gross vehicle weights	$\pm$10 percent

2. The WIM Smoothness Index

LTPP initially used a straightedge methodology and simulation of a straightedge with profiler data to evaluate WIM location smoothness. This proved limiting because of the need for lane closures, the time to do the straightedge evaluation, the poor match between the actual straightedge and simulated straightedge methods, and the need to more clearly define the quality of the pavement's smoothness. The WIM smoothness index is the result of two research projects conducted by the University of Michigan Transportation Research Institute (UMTRI) to develop an alternative to a straightedge smoothness methodology.

2.1 Initial Index Development

A study sponsored by the U.S Department of Transportation's Federal Highway Administration (FHWA) was undertaken by Steve Karamihas of UMTRI, under subcontract to MACTEC, to develop pavement smoothness criteria for LTPP WIM scale approaches (Karamihas and Gillespie, 2002). The guidelines for developing the index were: use of profiler data as collected by LTPP contractors, 5-axle tractor-trailer combination vehicles as the simulation population and a value for the index set so that the site would be expected to produce research quality data based on pavement conditions.

LTPP uses a 5-axle tractor semi-trailer combination vehicle to validate data from all Specific Pavement Studies (SPS) WIM sites along with a second truck that is site-dependent. The 5-axle truck is the most common type of heavy truck expected to pass over these locations as well as the majority of the truck population at most LTPP WIM sites. Overall, 616 combinations of layout, suspension, loading and tire options were included along with two damping levels and three speeds. The population was simulated over 61 longitudinal profiles collected on LTPP test sections to obtain the data to develop the original index.

Two pavement ranges stood out as influencing the scale errors. The short range, from –2.74 m before the scale to 0.46 m after the scale, and the long range, from –25.8 m before the scale to 3.2 m after the scale. As a result, two indices were generated – SRI (Short Range Index) and LRI (Long Range Index). The ranges determine which profile data goes into computing the index at the sensor. The two indices were then statistically related to WIM scale error but a high level of scatter was found. For this reason the index limit or threshold values were set very conservatively at 0.789 m/km by visual inspection of the plots of the 95th percentile error versus the index values.

The yes/no condition proved to be limiting in practice. The LTPP program had conducted profile evaluations on 30 WIM locations and WIM scale validations at 4 sites through June 2004. Only two of the pavements were below the threshold for research quality. None of the validation sites were below the threshold and yet two of them did in fact produce research quality data. It was determined that additional work, including a field validation and revised threshold(s), was appropriate.

a. Expanding the Index Application

A second study was approved by FHWA to do four things: replace the yes/no condition with a yes/no/maybe set of criteria, add a single unit truck to the simulation data set, use actual WIM section profiles to determine the impact of sensors on the index and validate the revised threshold values.

In the follow-up study (Karamihas and Gillespie, 2004) computed the 95 percent confidence limits on the errors using the data from the original study were determined. They are shown in Figure 1 by the lines extending from the origin. Having done that, alternate thresholds were established by taking the intercept of the confidence limits with the maximum errors allowed from Table 1. This approach permits the user to establish the threshold values based on the simulation results with respect to whatever they consider appropriate allowable errors.

Agencies frequently use single unit trucks when calibrating or validating WIM equipment. In order to expand the results of the original study three-axle single unit trucks were simulated. The runs included 218 combinations of vehicle properties at 3 speeds. A similar level of scatter existed for single unit trucks as for the 5-axle combination vehicles. The thresholds estimated using only the single unit truck population required smoother pavements for the same level of errors. The stiffer suspensions of dump trucks contribute to this outcome.

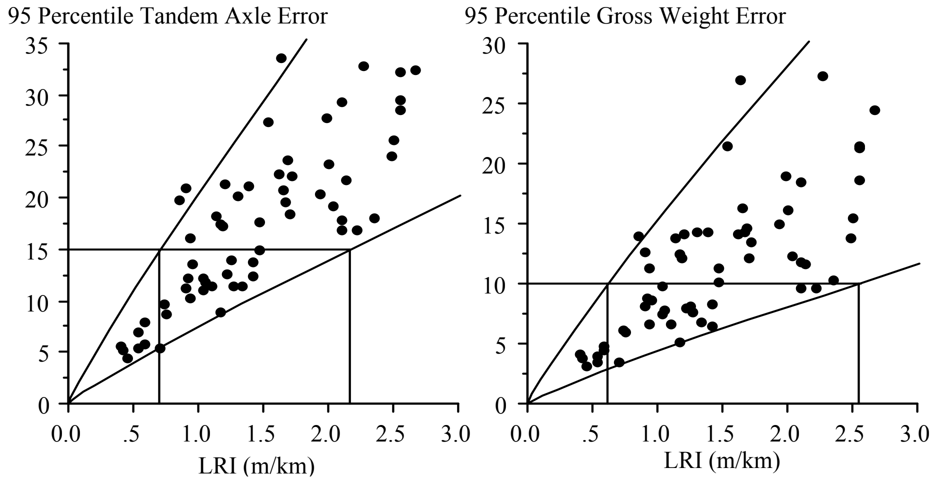

Figure 1 – Establishing Yes/ No / Maybe Index Thresholds (Karamihas and Gillespie, 2004)

The initial study had used general section profiles rather than WIM section profiles with the actual sensors to impact the simulated loads. Thirty-nine profiles from LTPP SPS WIM locations were considered in finalizing the index. Most of the locations had localized roughness, either narrow dips near the scale or a scale that was not flush with the surrounding pavement. Additional simulations were run to address localized roughness near the scale but not at the sensor itself. A third index referred to as Peak SRI was added to the criteria. It is the maximum SRI value in the length of the section between –2.45 m before the scale and 1.5 m after it.

The results of the simulation portion of the second phase are the threshold values proposed in Table 2. It was decided not to use the thresholds for single unit trucks that are more restrictive in making this recommendation.

Table 2 – Proposed yes/no/maybe thresholds

Index (m/km)	**Bound for Should Not**	**Bounds for May or May Not**	**Bound for Should**
LRI	Less than 0.5	0.5 to 2.1	Greater than or equal to 2.1
SRI	Less than 0.5	0.5 to 2.1	Greater than or equal to 2.1
Peak SRI	Less than 0.75	0.75 to 2.9	Greater than or equal to 2.9

3. Validation Process

A field evaluation was conducted at three locations near San Antonio, Texas from on May 4-6, 2004 (LTPP TSSC, 2004b). A total of twelve travel lanes were evaluated, all on Interstates. Eight were instrumented with class 1 bending plate WIM systems and four with piezo-electric systems. All travel lanes were surfaced with asphalt concrete. Each site was located on a relatively flat and straight section of road, suitable for a WIM scale. Speed limits were 110 km at each location.

Each vehicle performed 8 runs in each lane. At least two runs at each of three speeds was the target. Due to heavy volumes of high-speed traffic and slight upgrades located near some locations this target was not achieved for all truck-lane combinations.

3.1 Site Selection

The initial site selection criterion was four or more lanes of traffic at a site all instrumented with working WIM equipment. Sensor type, pavement and electronics were not considered part of the criteria since research quality data is not a function of those factors. Sites were then screened using outer lane IRI provided by the Texas Department of Transportation (TXDOT). After selection, a TXDOT profiler performed three runs at each of the lanes for the three sites identified by the screening process. For each of these runs both long and short range indices were calculated for left and right wheel paths. The computations were done using the LTPP WIM Smoothness Index software (LTPP TSCC, 2004c). The indices for the three runs were averaged to yield a single LRI and SRI value for each wheel path in each lane. The range of values for SRI, LRI and Peak SRI are shown in Table 3.

Table 3 – Range of index values at Texas validation sites

Site	LRI m/km		SRI m/km		Peak SRI m/km	
IRI (m/km)	Low	High	Low	High	Low	High
I-35 (1.10 – 1.74)	0.595	1.005	0.33	1.097	0.317	2.495
I-10 (0.76 - 0.85)	0.601	1.149	0.249	0.704	0.356	1.382
I-37 (0.86 – 1.09)	0.606	1.379	0.731	1.924	0.397	5.921

Test Vehicles

The simulation studies used both 5-axle combination vehicles and 3-axle single unit trucks. The test truck population for the validation had two of each. Available resources limited the number of trucks. The four trucks were:

a) A three-axle dump truck with steel leaf-spring suspension (3-axle – Steel). It was loaded to approximately 19, 100 kg with ‘pre-coat seal rock’.
b) A three-axle dump truck with steel leaf springs in the front and an air rear suspension (3-axle – Air). It was loaded to approximately 25, 000 kg with ‘pre-coat seal rock’.
c) A three-axle tractor with a two-axle extendable flat deck trailer (5-axle – Loaded). It was loaded with concrete traffic barriers to about 32, 950 kg. The suspension was air on all axles except for a steel leaf-spring suspension on the steering axle. This is the common truck in terms of suspension and loading for LTPP SPS WIM site validations.
d) A three-axle tractor with a two-axle flat deck trailer (5-axle – Partial). This is a TXDOT WIM calibration vehicle. It was loaded with concrete blocks to about 25, 900 kg. The tractor drive tandem axle group had an air suspension. All other axles had steel leaf-spring suspensions.

The dimensions of each truck were measured after loading and before and after test runs were performed at the sites. Weights of each axle group were obtained at certified scales before and after each day of testing. The static weights against which each WIM reading was compared were obtained by averaging the morning and afternoon weights of each axle group. Gross Vehicle Weight (GVW) was determined by adding the averaged weights of all axle groups.

4. Results

The sites selected were unable to fully test the proposed thresholds since no site had all its average index values in one of the three ranges.

The results are illustrated using the by truck results for tandem axle errors. The by truck computations are used because the index is based on the average errors for individual trucks not the errors based on a group of two or more trucks. Tandem axle errors are used because when the threshold values were identified thresholds based on the tandem axles were a more limiting condition than those based on GVW or single axles.

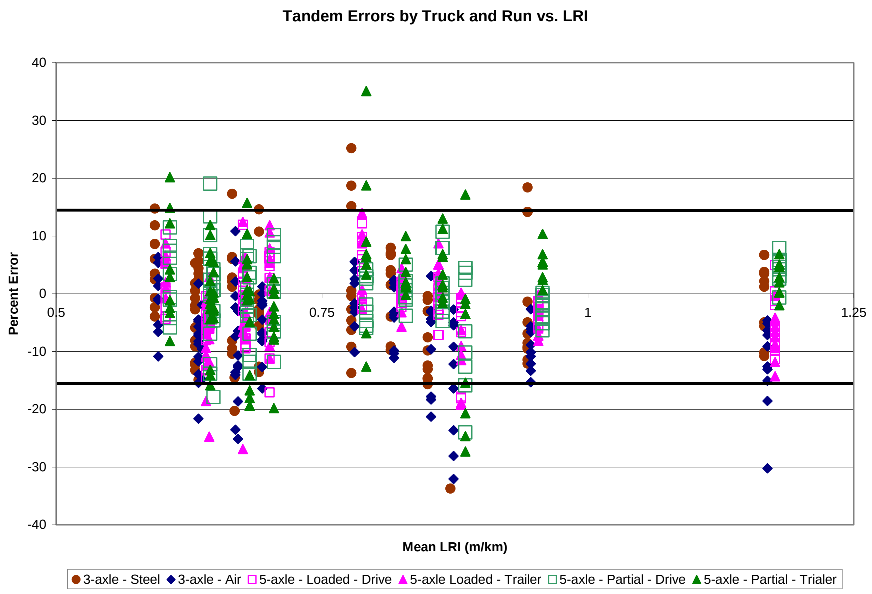

Figure 2 - Percent Error for Tandem Axles by Truck All Runs

Figure 2 shows the percent error for tandem axles for all runs plotted against the mean LRI value of each lane. The LRI values have been modified in the thousandths place to keep the trucks from overlapping each other completely. Additional horizontal lines have been added to show the ASTM limits that would be used (±15 percent) if the sites had been evaluated by that standard (ATSM, 2004) rather than LTPP's protocol (LTPP TSSC, 2001). Only eight of the twelve lanes are Type I by the ASTM criterion for tandem axles (and only one on the basis of GVW).

It was determined after the data were evaluated that none of the scales were unbiased. They were predominantly under-reporting loading characteristics. Therefore in doing the analysis the assumption was made that the bias could be made essentially zero and that in the process the variability would not change by more than a percent or so. This has been MACTEC's experience on other projects.

Error bounds are used for the remaining graphs discussed in this section. The error bounds all are based on the absolute value of two standard deviations of the mean error computed using population standard deviation and t-statistics for the 95% confidence limits due to small sample size. The error bounds are on the vertical axis and the index values on the horizontal axis. The graphs contain a thick horizontal line indicating the boundary for research quality data, 15 percent since all graphs are for tandem axles. There are also two solid vertical lines to indicate the threshold values for the index being plotted.

Figures 3 and 4 were developed to look at the effect of using the average of all the values of a specific index rather than some other descriptor such as minimum, maximum, etc.

Figure 3 is for the lightest test truck. In this case while the individual values span the entire range of the criterion, representing the index with the average (the open square) is consistent with the expectation that the site may or may not produce research quality data. Note that a range of average index values can be associated with approximately the same level of error.

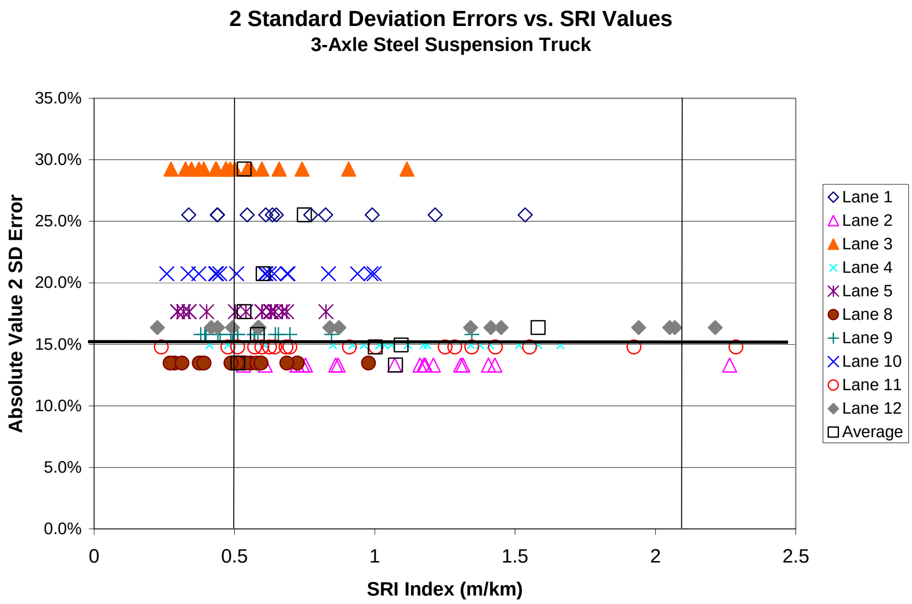

Figure 3 – Two Standard Deviation Values for Errors for the Lightest Test Truck vs. SRI for Each Pass and Wheel Path

Figure 4 is for the heaviest test truck. Once again the use of the average is consistent with the result may or may not produce research quality data. It should be noted that for the same index value, this vehicle is more likely to classify the site as producing research quality data.

Figure 5 shows error bounds by truck versus LRI. The LRI values for all these sites are in a narrow range. Very similar mean LRI values do not necessarily produce the same error bounds. It should also be noted that the lighter trucks, the dumps identified by the dot and the diamond, tend to have higher errors than the heavier combination trucks at the same LRI. The dotted vertical line in Figure 5 is the old threshold value. Based on this set of information it was set too high to determine if the data would be research quality based on pavement smoothness as defined by LRI.

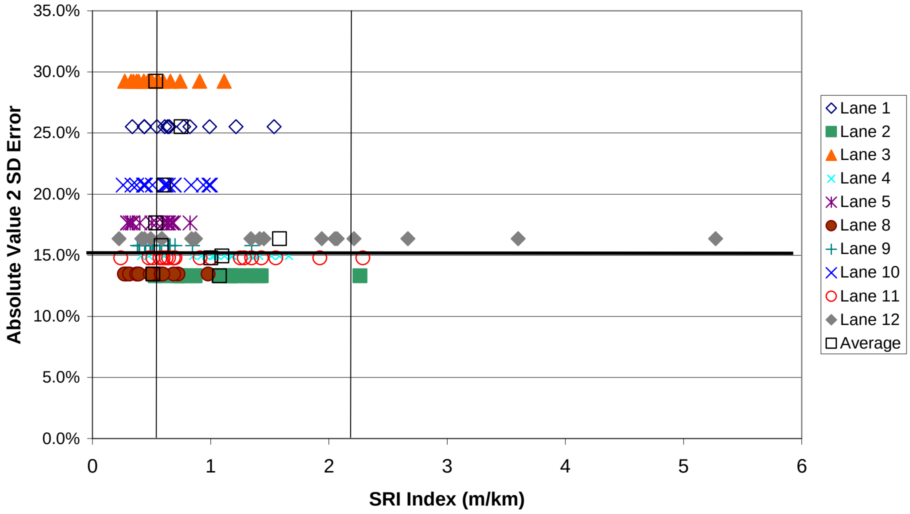

Figure 4 - Two Standard Deviation Values for Errors for the Heaviest Test Truck vs. SRI for Each Pass and Wheel Path

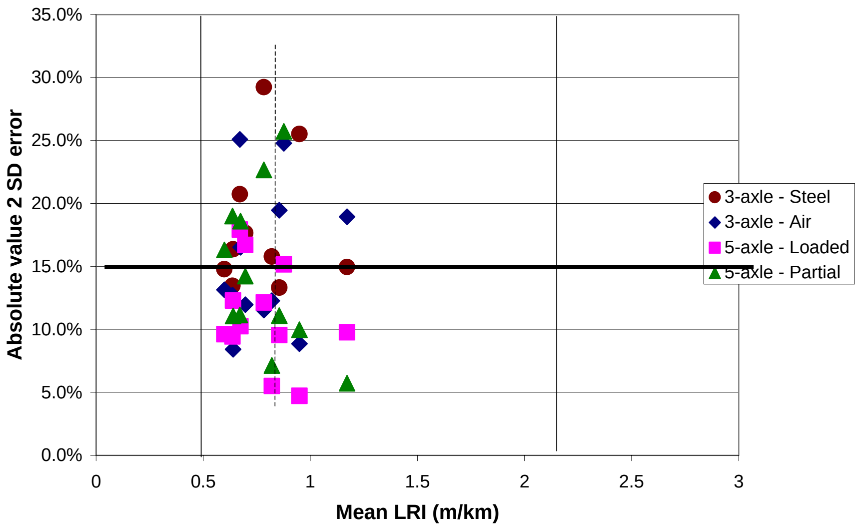

Figure 5 – Tandem Error Bounds versus Mean LRI values

Figure 6 shows the plot of the tandem error bounds versus SRI. Graphically it would appear that the threshold of 0.5 for SRI is slightly too high to be the boundary between the should not (no) and may or may not (maybe). There are two sets of data just below the threshold (0.47 m/km). However without lower values of SRI and all index values for a site(s) falling in the no category where the threshold should be moved to cannot be determined. The dotted vertical line in Figure 6 is the old threshold value. Based on this set of information it was set too high to determine if the data would be research quality based on pavement smoothness as defined by SRI.

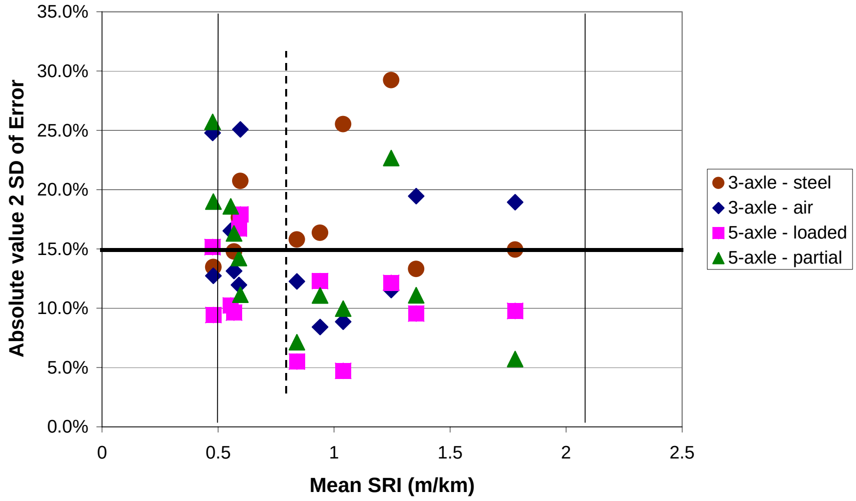

Figure 6 - Tandem Error Bounds versus Mean SRI Values

Figure 7 for Peak SRI indicates the possibility that the threshold between no and maybe is set too high. In this case there are far more cases (six) below the limit to support this interpretation. Here half the truck errors would qualify the site as research quality and the other half would not.

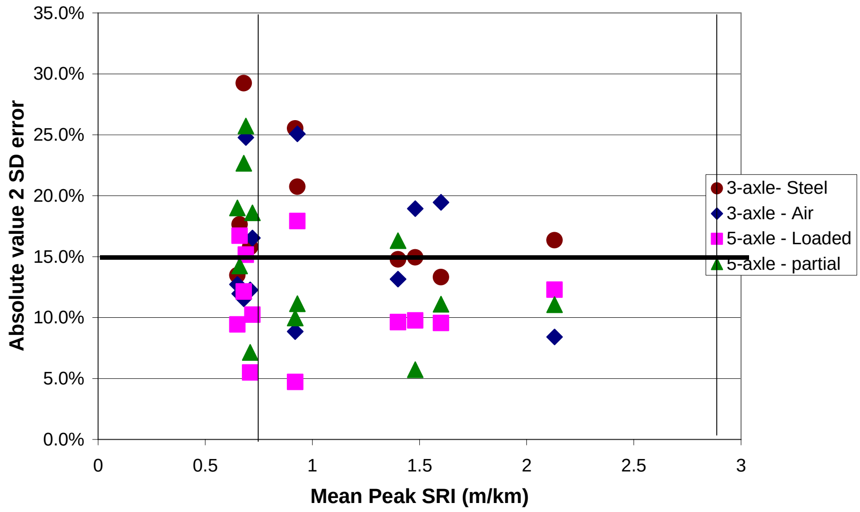

Figure 7 - Tandem Errors versus Mean Peak SRI

In none of the graphs could a direct relationship between data quality and the index be determined such that knowing the value of the index, the quality of the data could be estimated without using test trucks.

5. Conclusions

The initial criteria were not appropriate for determining the potential for research quality data. The sites selected and used for validation through May 2004 were all within the may or may not affect domain. Sites with similar index values and identical trucks did or did not produce data whose precision could be considered research quality by LTPP. As such the validation did not disprove the limits proposed.

The lower bounds for SRI and Peak SRI may be set too high. Sites that are so smooth that pavement smoothness should be considered for further validation work.

Unlike the lower bounds for the SRI and Peak SRI indices, there is no information on whether the upper boundary is close to reasonable. Additional validation with a really rough pavement by the indices described here should be done. A single lane in Ohio tested after completion of this paper, exceeded nearly all threshold values and produced research quality data.

Additional data should be collected on the smoothness index values and the outcomes of validations by LTPP. This data will be available through the SPS WIM validation and installation contracts currently being managed by FHWA. The fact that different trucks are used will be a confounding factor in expanding the evaluation. However more sites, particularly at the extreme index values, can provide additional insight on the appropriate limits for sections that should or could produce research quality WIM data for LTPP based on the pavement smoothness. The SPS WIM contracts are unlikely to provide data for very rough sites due to the selection criteria being used to determine when validations occur and where sites are installed. However, it is distinctly possible that "very" smooth sites will be identified particularly at installation locations with pavements built specifically for WIM installations.

The index is not a means to assign a measure of data quality to WIM data based on pavement smoothness.

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PLANNING AND TESTING OF INTEGRATED SYSTEM OF ELECTRONIC TOLL COLLECTION (ETC) AND WEIGH-IN-MOTION (WIM) ON FREEWAY

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Abstract

The main components of ETC include Automatic Vehicle Classification (AVC), Automatic Vehicle Identification (AVI) and Video Enforcement System (VES). In addition, Weigh-In-Motion (WIM) has been widely applied and incorporated into Commercial Vehicle Operations (CVO) with Automatic Vehicle Identification (AVI) technologies in Taiwan for more than ten years. With the integration of AVI and WIM technologies, the weight and safety check of commercial vehicles and drivers can been done in real time on highway main lanes under normal traffic speed. The objectives of this study include (1) developing the system architecture, (2) building up the system operating mechanism, and (3) carrying out the field testing of the system.

Keywords: Freeway, Electronic Toll Collection (ETC), Intelligent Transportation Systems (ITS), Weigh-In-Motion (WIM), Commercial Vehicle Operations (CVO).

Résumé

Les composants principaux d'ETC (collecte électronique des péages) incluent la classification automatique des véhicules (AVC), l'identification automatique des véhicules (AVI) et le système de contrôle par vidéo (VES). De plus, le pesage en marche (WIM) a été largement utilisé et incorporé dans la mise en œuvre de véhicules commerciaux (CVO) avec les technologies d'identification automatique de véhicules (AVI) à Taiwan depuis plus de dix ans. Avec l'intégration des technologies d'AVI et de WIM, la vérification des poids et de la sécurité des véhicules commerciaux et des conducteurs peut-être faite en temps réel sur les voies principales d'autoroutes à vitesse de circulation normale. Les objectifs de cette étude incluent (1) le développement de l'architecture du système, (2) la réalisation du mode opératoire du système, et (3) le test sur site réel du système.

Mots-clés: Autoroute, Collecte Électronique des Péages (ETC), Système de Transport Intelligent (ITS), Pesage en Marche (WIM), Mise en œuvre de Véhicules Commerciaux (CVO).

高速公路電子收費系統與動態地磅結合之規劃與測試

摘要：

電子收費 (Electronic Toll Collection, ETC) 之主要元件包括車輛自動分類技術 (Automatic Vehicle Classification, AVC) 、車輛自動辨識技術 (Automatic Vehicle Identification, AVI)，以及影像執法系統 (Video Enforcement System, VES) 。在台灣，將動態地磅 (Weigh-in-Motion, WIM) 及車輛自動辨識技術應用於商車營運系統 (Commercial Vehicle Operations, CVO)中已有十年以上的經驗。隨著車輛自動辨識及動態地磅技術之結合，主線道上之商車重量及其與駕駛者之安全檢驗可在正常之車速下即時執行。本研究目的包括(1)建立系統架構；(2) 建置系統運作機制；(3) 進行實地測試。

關鍵字：高速公路、電子收費、智慧型運輸系統、動態地磅、商車營運系統

1. Introduction

Taiwan's first Freeway has been opened to traffic since 1978. The second and third freeways jointed the service in 1993. The network functions as a toll system. It is known that Electronic Toll Collection (ETC) is one of the major developing fields of Intelligent Transportation Systems (ITS) in recent years. The main components of ETC are Automatic Vehicle Classification (AVC), Automatic Vehicle Identification (AVI) and Video Enforcement System (VES). Although the current toll collection is handled manually, a full scale field test of ETC in Taiwan had been conducted on National Freeway 3 from November 1998 to January 2001 by Chunghwa Telecom (CHT). A total number of 2500 passenger cars with transponders (on-board-unit) were tested during that time period. The test results indicate that ETC is highly feasible on the freeway system. In view of the successful outcome of the ETC field test, Taiwan's Ministry of Transportation and Communication (MOTC) decides to install the ETC system on the entire freeway network with private sector's participation. The contractor has signed the contract with Taiwan Area National Freeway Bureau, MOTC and scheduled to commence the ETC system in early 2006.

Under current freeway traffic control regulations in Taiwan, all loaded trucks must enter the weigh station that is located in both sides of each toll station for weight checking. Trucks equipped with or without OBU (On Board Unit) are all required to be pulled in for weighing, and the ETC does not provide any benefit to the driver in this weight checking due to the delay in the weigh house. In order to improve the commercial vehicle operation efficiency, using the ETC system alone is not sufficient. Some other technologies must be integrated with the ETC system to improve the weight check efficiency. The Weigh-In-Motion (WIM) is a possible solution. The purpose of this paper is to explore the possibility of integrating WIM and ETC. And the whole research was achieved with CHT, the ETC field test operator from 1998 to 2001 and using their ETC system.

2. Related Projects Review

WIM has been widely applied for many decades and incorporated into Commercial Vehicle Operations (CVO) with AVI technologies, a sub field under ITS. With the integration of AVI and WIM technologies, the weight and safety check of commercial vehicles and drivers can be done in real time on highway main lanes under normal traffic speed. Those trucks that passed all the checks need not be pulled into the weigh station. There will be a significant reduction in travel time for commercial vehicles, and highway patrols can focus more on trucks that may violate the weight and/ or other vehicle regulations. Currently, there are three major CVO systems, PrePass (HELP Inc., 2002), Oregon Green Light (Oregon DOT, 2002), and NORPASS(NORPASS, 2002), have been operated in North America since mid 90's and the benefits have been proved.

Both PrePass and Oregon Green Light are oriented from a research project, called HELP (Heavy Vehicles Electronic License Plate), started in 1983 (WHM Transportation Engineering Consultants, Inc., 2002). Field trial of HELP project was called Crescent Project started in 1989 at I-5 and I-10. When the Crescent Project ended in 1994, a public-private-partnership company, named HELP, Inc. was established. The Crescent Project was changed to the name of PrePass System and began it commercial operation since 1996. PrePass system has become the largest

CVO system in North America. There are around 200 operation sites in 21 states in the U.S. and more than 200,000 trucks participate in this system (HELP Inc., 2002).

Oregon, also a member state of Crescent Project, decided to operate their CVO system after the project ended with the funding from federal government. Their system is called Oregon Green Light. There are 21 weigh stations in Oregon State installed with CVO equipment and about 1,900 trucks participate in this system in 2001 (NORPASS, 2002). In addition to the above two systems, the NORPASS system is newly organized. The system is formerly called Advantage I-75. NOPPASS has five member states, eight partner states in the U.S. and one partner province in Canada currently (Oregon DOT, 2002).

The technologies used in Prepass, Green Light, and NORPASS are very similar. Main lane WIM systems, as well as AVI antennas, are installed at upstream of the weigh station. All trucks equipped with AVI transponders would have a safety and registration check when they pass the system. The weight of the truck, safety records, and registration data are compared with the preset criteria. Those who cannot meet any of the criteria will be asked to pull in the weigh station by sending message back to the transponder.

3. System Architecture

The architecture of the whole system is shown as Figure 1. It is composed of four sub-systems, namely roadside sub-system, vehicle sub-system, administration sub-system, and external sub-system. Each sub-system will be described in detail in the following sections.

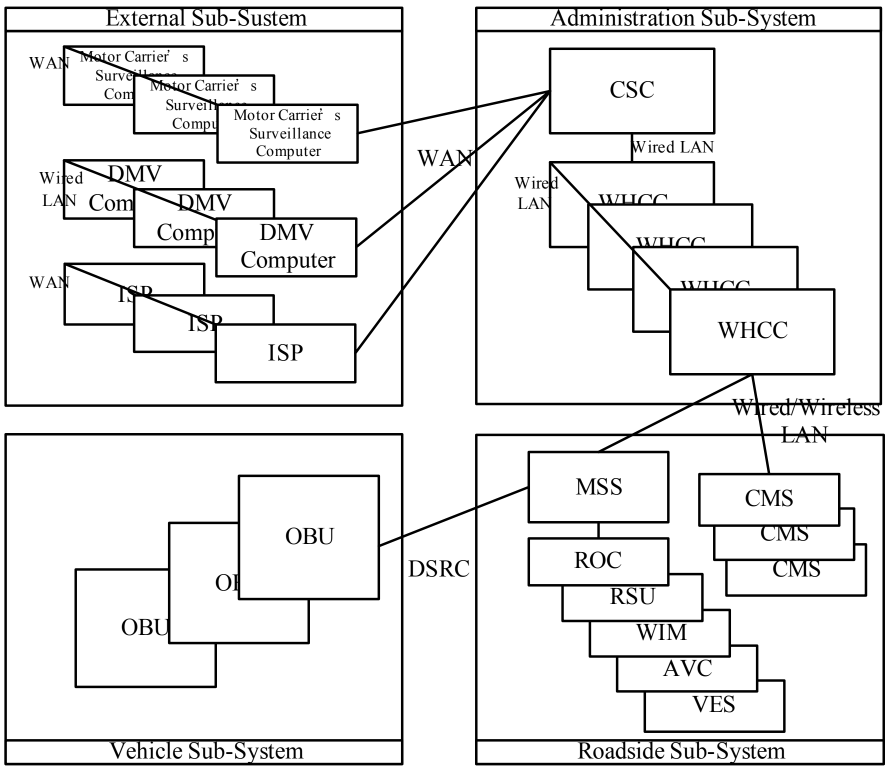

Figure 1 - System Architecture

3.1 Roadside Sub-system

The roadside sub-system is composed of several Changeable Message Sign (CMS) and the Main-lane Surveillance Station (MSS). The primary function of CMS is to provide travel information to road users and they are directly controlled by the Central Surveillance Center (CSC). The MSS installed at the main-lane of highway is controlled by the nearest downstream Weigh House Control Center (WHCC). The MSS consists of Weigh-in-Motion (WIM) system, Roadside Unit (RSU), Automatic Vehicle Classification (AVC), Vehicle Enforcement System (VES), Roadside Operation Computer (ROC).

3.2 Vehicle Sub-system

The On-Board Unit (OBU) is the major component of the vehicle sub-system. With the use of OBU, the ETC transaction and truck weight and safety record check can then be processed. The OBU must be capable of displaying “red” and “green” lights on the small LCD screen or providing different sounds to indicate the various checking statuses to drivers.

3.3 Administration Sub-system

The administration sub-system is composed of the Weigh House Control Center (WHCC) and Central Surveillance Center (CSC).

- Weigh House Control Center (WHCC): The WHCC is located in the weigh house near the toll station and operated by the highway patrols. This system controls all the following sub-systems and the upstream MSSs. The computer system used in the weigh house is called Weigh House Computer (WHC) which controls the static weigh pad, truck record checking sub-system, violation citation sub-system, traveler information sub-system, and fleet management sub-system. The relationship among the WHCC, toll station, and MSSs is illustrated in Figure 2.
- Central Surveillance Center (CSC): The CSC comprises the truck surveillance sub-system, weight analysis sub-system, and traveler information providing sub-system.

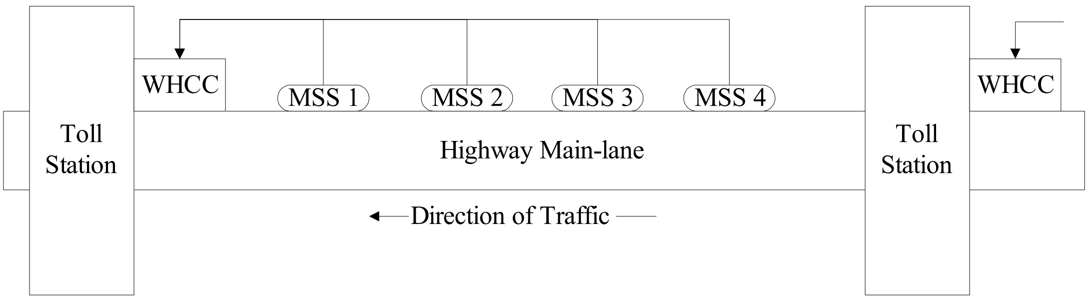

Figure 2 - The Relationship between WHCC, Toll Station, and MSS

3.4 External Sub-system

The external sub-system comprises the truck company’s surveillance computer, DMV computer, and traveler information service provider.

3.5 Data Flow

The proposed data flow chart of major components is shown in Figure 3.

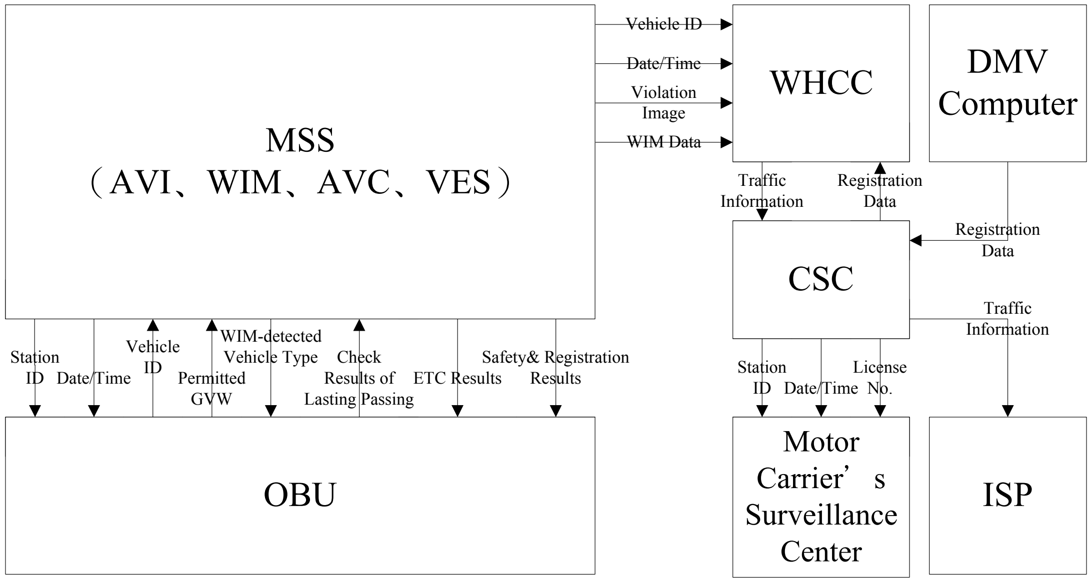

Figure 3 - Data Flow Chart of the Integrated System

3.6 Communication Protocols

Data transmission of the integrated system is achieved by Wireless LAN, Wired LAN, WAN (Wide Area Network), and DSRC (Dedicated Short Range Communication).

4. System Operating Mechanism

There are five operational functions developed in this integrated system, they are

- pre-screening the overloaded trucks,
- monitoring the specially permitted vehicles,
- checking trucks’ safety and registration records,
- overspeeding enforcement, and
- executing the ETC transaction.

Figure 4 illustrates the flowchart of all the functions, and each function is described below in detail.

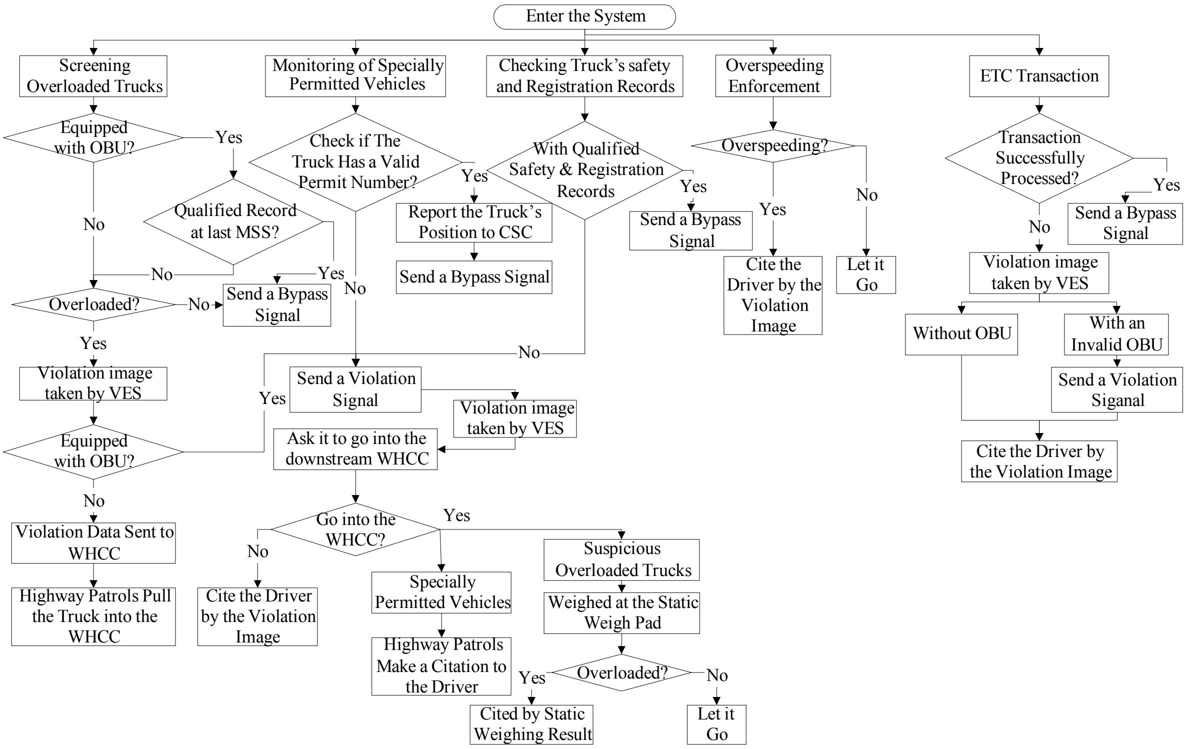

Figure 4 - Flowchart of all System Functions

4.1 Pre-Screening the Overloaded Trucks

For any truck equipped with OBU its ID, the weight checking results as well as check time at last MSS or static weight house, and other necessary truck information will be identified by the DSRC communication between the OBU and RSU. At the mean time the truck is weighed by the WIM at the MSS site. If the time gap of passing this MSS and the upstream weight check point is within the preset tolerable limit, and the truck meets the bypass criteria earlier, say with a qualified record, a bypass signal (green light) will be given again to the truck through the second RSU to OBU.

If the time gap of passing this MSS and the upstream checking point is not within the preset tolerance, the ROC will compare the weight detected by the WIM and the legal gross weight limit obtained from the OBU. If the truck is identified as a suspicious overloaded truck, the VES will start and take the photo of the truck immediately. All the data will then be transmitted to the downstream WHCC. If the truck passes all the checks (including other checks described above), a bypass signal will be given to the truck through the second RSU to OBU. Otherwise, the truck will receive a violation signal (red light) and be pulled into the WHCC. The suspicious overloaded truck will be weighed again by the static weigh pad at the WHCC for double check.

At the initial stage of system implementation, the MSS will be only installed at 800m~1000m upstream the WHCC for the pre-screening purpose (indicated as MSS 1 in Figure 2). For further system implementation, the MSSs can also be installed at other highway main-lane locations, such as MSS 2, MSS 3, and MSS 4 in Figure 2. For any truck equipped with OBU and being detected as a suspicious overloaded one, it will be pulled into the nearest downstream weigh house. If the truck does not comply with this order, the system will automatically send an overloaded violation citation to the driver. In order to prevent any mis-citation, a higher threshold value shall be used in these MSSs.

For trucks not equipped with OBU, the truck type can be classified by the WIM and the weight can be detected. Detected data and photo image, if the truck is considered overloaded by comparing the WIM data with the rough estimation based on the truck type, will be sent to the WHC in real time for further analysis. Trucks without OBU are requested to go through the downstream weight house at no choice.

4.2 Monitoring of Specially Permitted Vehicles

For any vehicle that need a special permit to use highway, it is required to equip with OBU and its license plate number will be stored in a dedicated database. When any OBU-equipped truck passes the MSS, it will be checked to see if it has the right permission to operate on the highway. If the truck has a valid permit number, the position of the truck will be reported to the CSC via the WHC. Otherwise, the VES will take a picture of this truck and the highway patrols at the weigh house will be notified. The truck will then be pulled into the WHCC. If the truck fails to comply with the order, a citation will be made by the highway patrol using its violation image.

4.3 Checking Trucks' Safety and Registration Records

The safety and registration record of each OBU-equipped truck will be checked each time it passes the MSS. If the truck has no qualified safety and registration records, the driver will be notified by a fail signal, and the highway patrols will also be informed at the same time. The truck will be pulled into the WHCC.

4.4 Over-speeding Enforcement

The AVC installed at each MSS is capable of detecting the vehicle's speed. If any passing vehicle is over-speeding, it will be detected by the AVC. The over-speeding vehicle will be pictured by the automatically engaged VES. All the violation information including the image of that vehicle will then be transmitted to the downstream WHCC. It will be cited by the highway patrols.

4.5 Executing ETC Transaction

The ETC transaction will automatically be processed when any OBU-equipped truck passes the system. Trucks who equipped with invalid OBUs will be pictured by the VES and it will also be cited by the highway patrol at the WHCC.

5. Field Trial of the System

A full-scale field trial of the integrated system was conducted on National Freeway No.3. The system was installed 1000m upstream Long-Tan north-bound weigh house. Two major truck types, four axle semi-tractor trailer (2S2) trucks and single unit trucks (U11), are used in the field test. A total number of six trucks equipped with OBUs were tested for 140 runs in the test site. The combination of truck loading condition and running speed is shown in Table 1. The major objectives of the field trial are to verify the technological feasibility of the system and to evaluate the bypass threshold of this system. Due to the budget constraints, only portable WIM systems can be considered. South Africa made, Truvelo capacitive mats were selected for this test. The GVW bias is ±15% from the vendor's brochure. The test results are also shown in Table 1 and detail description is given below.

5.1 Technological Feasibility Verification of the System

All system functions have been tested and verified at the CHT research lab. During the field trail test the outcomes are relatively satisfied with only two kinds of system malfunctions, mismatch of WIM and OBU data and defect of OBU. However, the problems were solved during the trial test.

Mismatching of WIM and OBU data

If two trucks of the same type passed the system with headway less than the minimum required matching time, i.e. 8 seconds in this trial test, the WIM and OBU data would be mismatched. In this situation, if both trucks were equipped with OBUs, the WIM data of the first truck would be matched to both trucks. If only the followed truck was equipped with OBU, the WIM data of the first truck would be matched to the followed one. If both are not equipped with OBU, the WIM data of the first truck cannot do any match. It is found that the problem was due to the data matching logic used in this system and it was solved during the test period.

Defect of OBU

OBU malfunction happened once during the trail test. It was mainly due to the inefficient communication between OBU and RSU. Due to environmental constraints, the RSU was hung on the light post along the freeway. It is suggested the RSU be installed on an overhead or cantilever gantry in order to enhance the communication efficiency.

5.2 Bypass Threshold Analysis

Another objective of the trial test is to study the appropriate bypass threshold that can screen as many overloaded trucks as possible and minimize the number of mis-screened trucks that being pulled into the weigh house. The concept of threshold selection can be seen in Figure 5.

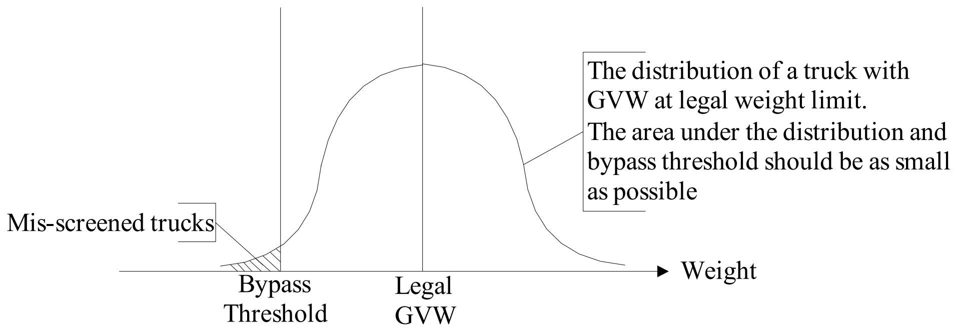

Figure 5 - The Concept Diagram of Threshold Selection

For a given truck with a GVW equals to the legal GVW limit, it might be weighed higher or lower with a normal distribution. The lower the bypass threshold is set, the lower the mis-screened trucks. A 5% mis-screened trucks with GVW equals to the legal GVW limit has been pre-defined. For a normal distribution, it implies a two-tail 90% confidence interval or a one-tail 95% confidence interval. The *Accu* is then defined as the relative error of WIM at a one-tail 95% confidence interval and the threshold can then be defined as Equation (1)

$$Th = GVW \times (1 - Accu) \tag{1}$$

where: Th : Bypass threshold

GVW : Legal gross vehicle weight

$Accu$: Accuracy of WIM system at a one tail 95% confidence interval, expressed as ± %

The accuracy of the WIM used in this field test at confidence interval of 90% is ±14.3 %. The low accuracy is primarily due to the characteristics of selected WIM type. According to this value, the bypass thresholds of 2S2 and U11 are 30.00 tons and 12.86 tons, respectively. The screening outcome of this field-test is shown in Table 1. If a more accurate WIM were used for the test, the threshold values could be increased so as to more close to the legal weight limits. In this case only the trucks that have loaded close to the legal limits will be pulled into the weight house. The efficiency of the whole system can be significantly improved under this condition.

As seen in Table 1, most of the test runs are classified as "Fail" because most the tested trucks were loaded above the selected threshold values. The average accurate rate of the trial test for 2S2 is 95% for both test speeds. And the average accurate rate for the U11 is 86.7%. The overall accuracy of the trial test is 91.4%. The outcomes reveal that this trial test has very successful results. The "miss rate" (overloaded vehicles not selected by the pres selection system as a proportion of all overloaded vehicles) cannot be calculated from the tests because all test vehicles were not overloaded. Since the actual weight of all test trucks are higher than their bypass threshold, the "wrong detection rate" (vehicles whose GVW are less than the bypass threshold selected by the pre selection system as a proportion of all selected vehicles) are equals to 0%.

Table 1 - The screening outcome of the field test

Truck Type	**Legal GVW (tons)**	**Actual GVW (tons)**	**Truck Speed**			
			80KPH		60KPH	
			No. of Screening Outcome		No. of Screening Outcome	
			OK*	Fail*	OK*	Fail*
S112	35.0	31.0	4	6	0	10
		33.5	0	10	0	10
		33.8	0	10	0	10
		34.0	0	10	0	10
U11	15.0	12.0	9	1	7	3
		13.0	3	7	1	9
		14.9	0	10	0	10

*: OK means the truck receives a by-pass" signal, and Fail means the truck needs to enter the WHCC.

6. Conclusions and Recommendations

In this study, the concept and architecture of the integrated system, as well as the system operating mechanism, have been developed. The architecture of the system comprises the roadside sub-system, vehicle sub-system, administration sub-system, and external sub-system. And the operating mechanism can be divided into five major parts, i.e. screening overloaded trucks, monitoring of specially permitted vehicles, checking trucks' safety and registration records, over-speeding enforcement, and ETC transaction. Through the field trial of the prototype system, the technical feasibility of the system is verified. The following recommendations are made,

- Explore accuracy requirement to meet the enforcement evidentiary needs: Due to the budget constraints, only portable WIMs can be used. And larger scale field test should be done with higher accuracy WIM to explore accuracy requirement to meet the enforcement evidentiary needs.
- Development of a high-accuracy WIM system and an automatic calibration mechanism: The WIM system accuracy is crucial for the total system performance. Research efforts should be put on the development of a high-accuracy WIM system. Through the implementation of the system, a huge amount of WIM and static weigh pad data can be collected. The relationship between the WIM and static weigh pad data can then be clarified. An automatic calibration mechanism could be developed from the research outcome.
- Implementation study of DSRC technology on other commercial vehicle operations: The DSRC technology has been widely used in electronic toll collection. Besides the implementation mentioned in this study, the application of DSRC in other CVO fields, shall also be investigated.

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DEVELOPMENT OF INTEGRATED PERFORMANCE MODEL FOR INTEGRATED SYSTEM OF ELECTRONIC TOLL COLLECTION (ETC) AND LECTRONIC SCREENING (ES) ON FREEWAY



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Abstract
The main objective of this study is to develop the performance model that integrates delay time reduction (efficiency index) and conflict volume reduction (safety index) for integrated system of Electronic Toll Collection (ETC) and Electronic Screening (ES) with Weigh-In-Motion (WIM) on freeway. Some possible integrated layouts of ETC and ES are analyzed firstly. A toll plaza simulator TPS is utilized to simulate the delay condition and compute average delay time of each commercial vehicle according to different integrated layout scenarios. The traffic conflicts analysis model is also developed to compute the traffic conflicts reduction performance. Some results from this study could provide useful evaluation basis for ETC and ES deployments in Taiwan.

Keywords: Performance Model, Electronic Toll Collection (ETC), Electronic Screening (ES), Weigh-In-Motion, WIM.

Résumé
L'objectif principal de cette étude est de développer le modèle de performance qui intègre la réduction des temps de retard (indice d'efficacité) et des conflits (indice de sécurité) pour les systèmes de collecte électronique de péage (ETC) et de vérification électronique (ES) avec pesage en marche (WIM) sur les autoroutes. Quelques formes/conceptions/architectures intégrées de ETC et ES sont d'abord analysées. Un simulateur de station de péage (TPS) est utilisé pour simuler la condition de retard et pour calculer le temps de retard moyen de chaque véhicule commercial selon les différents scenarii d'architecture intégrée. Le modèle d'analyse des conflits de circulation a aussi été développé pour calculer la performance de la réduction des conflits de circulation. Quelques uns des résultats de cette étude peuvent fournir une base d'évaluation utile pour le déploiement de ETC et de ES à Taiwan.

Mots-clés: Modèle de Performance, Collecte Électronique de Péage (ETC), Vérification Électronique (ES), Pesage en Marche (WIM).

電子收費與電子篩選整合系統之整合績效模式發展

摘要：
此研究之主要目的爲發展在高速公路上結合動態地磅 (Weigh-in-Motion, WIM) 系統之電子收費系統 (Electronic Toll Collection, ETC) 及電子篩選 (Electronic Screening, ES) 之績效模式；該模式包括減少延滯時間（效率指標）及減少交通衝突量（安全指標）。本研究首先針對 ETC 及 ES 的一些可能的配置形式進行分析，並使用收費區分析軟體 TPS 根據不同的之配置情境進行模擬，以探討延滯之情況並計算每輛商車之平均延滯時間。本研究同時建立交通衝突分析模式，以計算交通衝突減少的績效。本研究之相關成果可作爲台灣在佈設 ETC 及 ES 之參考。

關鍵字：績效模式、電子收費系統、電子篩選、動態地磅

1. Introduction

Electronic Toll Collection (ETC) on freeway is one of the nine developing areas of Intelligent Transportation Systems (ITS) in Taiwan. The Electronic Screening (ES) that integrates Weigh-in-Motion (WIM), static weigh station and Automatic Vehicle Identification (AVI) technologies is one important subsystem of Commercial Vehicle Operations (CVO). Both ETC and ES are developed to finish the toll payments and check the weight and safety of driving vehicles (especially for commercial vehicles) automatically by utilizing information and communication technologies. The major benefits of ETC and ES includes travel time saving and traffic flow conflicts reduction. With the same AVI technology of ETC and ES, these two systems could be integrated to achieve "shared software/hardware items, multiple functions" effectiveness. The feasibility test of the integrated system of ETC and ES has also been implemented in Taiwan.

In addition to the "shared software/hardware items, multiple functions" effectiveness, it is also necessary to integrate ETC and ES on the freeway systems in Taiwan due to the special layouts of toll collection plazas and weigh stations. The weigh stations are installed at the near upstream or downstream of toll collection plazas on the freeway systems. Since the distance between the weigh station and the toll plaza is short, commercial vehicles still have to enter the roadside static weigh station immediately before or after passing the toll collection plaza. Not only the travel time couldn't be saved effectively but also the weaving conflicts will be increased while commercial vehicles change lanes to enter the roadside static weigh station. The truck transportation benefit and effectiveness of ETC or ES deployments on freeway systems in Taiwan will only happens when we integrate these two systems.

In order to evaluate the benefit of ETC and ES integrated system, this study tries to develop a performance model with delay time reduction (efficiency index) and conflict volume reduction (safety index). Since there are some different possible integrated layouts of ETC and ES, we use a toll plaza simulator TPS to simulate the delay condition and compute average delay time of each commercial vehicle according to different integrated layout scenarios. A traffic conflicts analysis model is developed to compute the traffic conflicts reduction performance.

2. Benefit of ETC and ES

Electronic Toll Collection (ETC) is the system provides for automatic collection of toll revenue through the application of in-vehicle, roadside, and communication technologies to process toll payment transactions (FHA, 2000). The major purpose of ETC deployment is to provide the capability for vehicle operators to pay tolls without stopping their vehicles. There are usually three subsystems in an ETC system: Automatic Vehicle Identification (AVI), Automatic Vehicle Classification (AVC) and Video Enforcement System (VES). Essentially, ETC equipment substitutes for having a person, or coin machine, manually collect tolls at tollbooths. The highway 407 in Toronto is the world's first all electronic toll highway (ITS, 2001).

Electronic Screening (ES) is one of the three areas in American's ITS/CVO (Richeson, 1999). It is deployed to automatically screen vehicles as they approach weigh stations and allow those that are safe and legal to bypass without slowing down or stopping. The capability requires installation of WIM scales in the main highway to measure the weight of trucks while they are moving at highway speeds. The trucks would be equipped with Dedicated Short Range Communication (DSRC) transponders (On-Board-Unit, OBU) that can be read and written by roadside readers (Roadside-Unit, RSU) just before the vehicle goes over the scale. This first reader obtains identifying information from the transponder equivalent to the license plate number. The process described above is also called the AVI process. A Roadside Operations Computer (ROC) in the weigh station uses this identifier to check the legal weight information about this vehicle. If the weight is good, the second reader sends back a message to the transponder that says the truck is cleared and does not need to pull into the static scale ramp. The transponder is usually mounted on the dashboard and has red and green indicators. The green light signals the driver to proceed and the red light to pull into the scale. Enforcement personnel can set up the ROC to pull in a certain number of vehicles for random safety inspections. Figure 1 shows the ES system layout and operational concept.

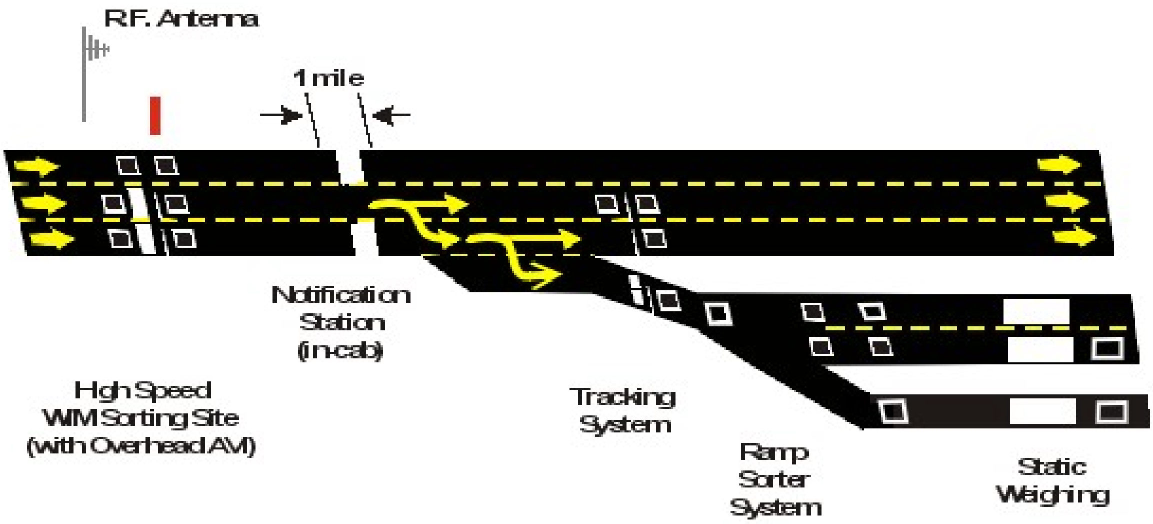

Figure 1 – ES System Layout and Operational Concept
(http://www.odot.state.or.us/trucking/its/green/light.htm)

With the same AVI and AVC technology, ETC and ES could be integrated to a system to provide multiple benefit of ETC and ES. The benefit of several ETC and ES deployment case studies are summarized in Table 1.

Table 1 – Benefit of several ETC and ES deployment case studies

System	Case Studies	Benefit
Electronic Screening (ES)	American PrePass System (http://www.prepass.com)	1.Increase customer satisfaction. 2.Reduce operational cost. 3.Increase operational efficiency. 4.Increase driving safety and promote operator's public image. 5.Attract more excellent drivers.
	American Green Light System (http://www.odot.state.or.us/trucking/its/green/light.htm)	1.Reduce unnecessary stopping time. 2.Provide better work environment for truck drivers to attract more excellent drivers. 3.Reduce fuel consumption due to trucks stop to weigh. 4.Increase highway safety. 5.Reduce manpower requirement.
Electronic Toll Collection (ETC)	Japanese Odawara Toll Gate (Proper, 1999)	The conventional toll collection takes 14 seconds per car on average. ETC takes only about 3 seconds per car. The time saving is 11 seconds per car on average.
	Canadian 407 Highway (ITS, 2001)	The efficiency and safety are improved.
	ITS America Studies on Electronic Payment Systems (ITS, 2001)	1.Reduce labor requirement. 2.Improve traffic congestion at toll plazas and increase throughput of toll facilities. 3.Increase the convenience and ease of use for customers. 4.Reduce stopping, wait and payment time. 5.Increase the variety of payment options (cash, credit card, automatic bank transfer, post-payment etc.). 6.It is easy to establish a flexible pricing based on time of day, congestion levels, vehicle occupancy and distance traveled. 7.Provide the capability of integration with other transportation electronic payment system applications. 8.Improve air quality and fuel consumption at toll plazas.

3. Development of Analytical Integrated Performance Model

3.1 The analytical integrated performance model

"Reduce unnecessary stopping or waiting time" and "Increase driving safety" are two major benefit of ETC and ES deployments. The analytical integrated performance model is developed to analyze delay time reduction (efficiency index) and conflict volume reduction (safety index) of truck transportation for the ETC and ES integrated system. Figure 2 shows the process of the developed model.

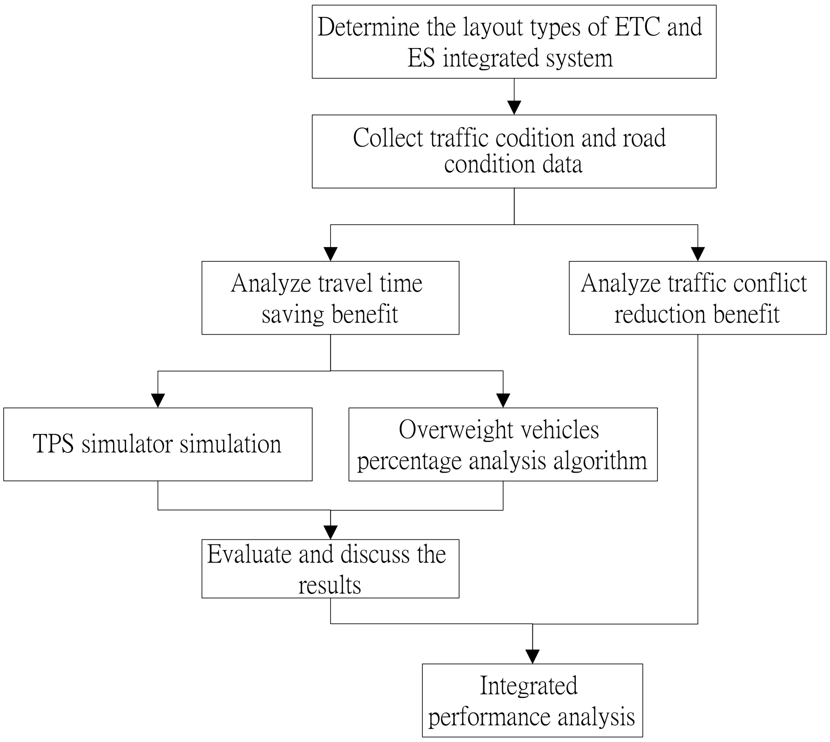

Figure 2 – Process of the Analytical Integrated Performance Model

There are three major analysis models in Figure 2: overweight vehicles percentage analysis algorithm, TPS simulator simulation and traffic conflict analysis model. The analysis process and characteristics of each model are described in the following sections.

3.2 The Overweight Vehicles Percentage Analysis Algorithm

The overweight vehicles percentage analysis algorithm is as Figure 3. This algorithm is developed to analyze the time saving of non-overweight (legal) heavy vehicles under ETC, ES, ETC&ES conditions. By comparing with the base condition (without ETC and ES) that all heavy vehicles on the freeway must be pulled into the static weigh station when they pass through the toll plaza, non-overweight heavy vehicles equipped with ETC or ES OBU could save their toll payment time or weighing time.

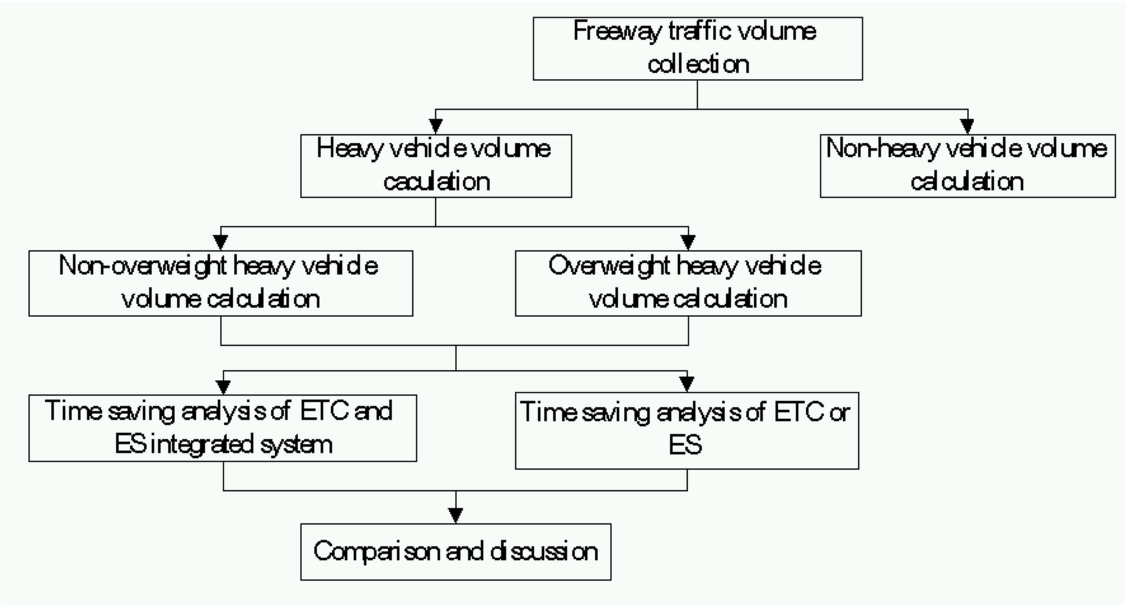

Figure 3 – Process of the Overweight Vehicles Percentage Analysis Algorithm

3.3 The TPS Simulator Simulation

Figure 4 is the process of TPS simulator simulation. TPS (Toll Plaza Simulation) is a simulator developed to simulate the traffic flow condition of toll plazas on the freeway in Taiwan. Since the weigh station on the freeway is installed around the toll plaza in Taiwan, TPS can also simulate the delay time from passing toll plaza to entering weigh station of heavy vehicles. The TPS simulator simulation process is developed to analyze time saving by different percentage of heavy vehicles equipped with OBU and different percentage of overweight heavy vehicles.

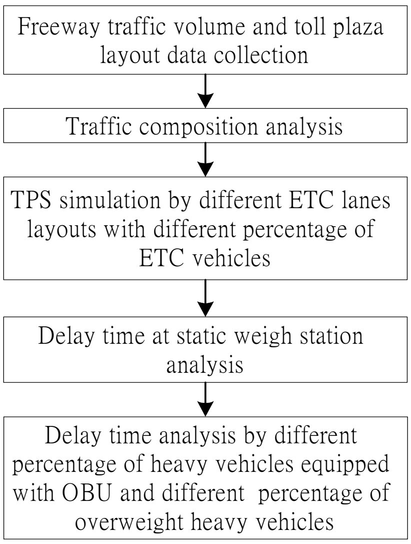

Figure 4 – Process of the TPS Simulator Simulation

3.4 The Traffic Conflict Analysis Model

The process of the traffic conflict analysis model is as Figure 5. This model is developed to analyze the conflict volume of heavy vehicles and other type vehicles (passenger car, bus etc.) when they have to change lane to enter the weigh station (see Figure 6). Since non-overweight heavy vehicles equipped with OBU need not to change lane to enter the weigh station, the traffic conflict volume will be reduced. Reduction of conflict volume by different percentage of heavy vehicles equipped with OBU and different percentage of overweight heavy vehicles is calculated.

Freeway traffic volume and toll plaza layout data collection

↓

Lane utilization percentage of each vehicle type analysis

↓

The conflict volume of heavy vehicles and other type of vehicles analysis

↓

Conflict volume analysis by different percentage of heavy vehicles equipped with OBU and different percentage of overweight heavy vehicles

Figure 5 – Process of the Traffic Conflict Analysis Model

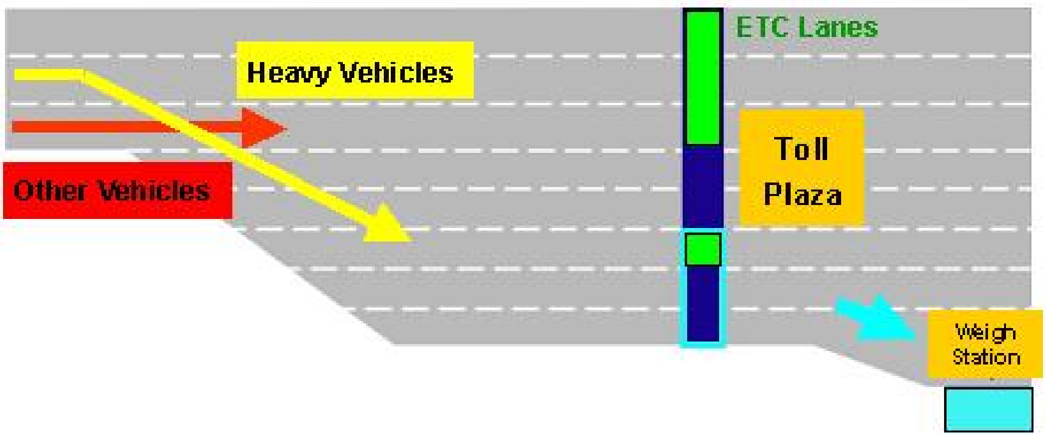

Figure 6 – Traffic Conflict of Heavy Vehicles and other Vehicles at Toll Plaza

4. Case Study

In the case study, we select the Yangmei toll station on the Sun Yat-sen freeway as the example to apply the integrated performance model to analyze the benefit of integrated system of ETC and ES. From the traffic volume survey in 1997~2000 of one research (Liao, 2002), percentage of each vehicle type passing through the Yangmei toll station is summarized as Table 2. The peak hourly volume is assumed 7,000 vehicles in two hours.

Table 2 – Percentage of each vehicle type passing through the Yangmei toll station

Non-heavy vehicle		**Heavy Vehicle**	
Small Vehicle	Bus	Truck	Tractor-trailer
79%	6%	7%	8%

4.1 Time Saving Benefit Analysis

The overweight vehicles percentage analysis algorithm

From some survey reports (Chou, 1998, 2002), the percentage of overweight heavy vehicles is 4.633% and the average weighing time of each heavy vehicle is: maximum: 22 seconds, minimum: 4 seconds, average: 11.18 seconds. By utilizing the algorithm, assume all heavy vehicles have been equipped with OBU and the time saving in different conditions is calculated as Table 3.

Table 3 – Time saving benefit of ETC and ES through the overweight vehicles percentage analysis algorithm analysis

Unit: seconds/2 hours

	Without ES and ETC	**ES**	**ETC**		**ETC + ES**	
			By ticket	**By cash**	**Min. benefit**	**Max. benefit**
Non-overweight heavy vehicle	—	11195	0~300	0~8411	11495	19606
Overweight heavy vehicle	—	0	0~300	0~8411	300	8411

The TPS simulator simulation

By utilizing the TPS simulator, we simulate the time saving by different percentage of heavy vehicles equipped with OBU and different percentage of overweight heavy vehicles. The basic parameters are set as below:

- Site: south bound lanes at the Yangmei toll station
- Toll gates: 8 (present 7 + 1 assumed heavy vehicle ETC lane)
- Simulated time interval: 15 minutes × 8, simulate 5 times
- Traffic volume: 875 veh/15 min (i.e. 7000 veh/2 hour)
- Average speed of each vehicle through the toll station: 60 KPH
- Average free flow speed of heavy vehicle at the enter section of weigh station: 25 KPH
- Toll collection time: (see Table 4)

Table 4 – Toll collection time of each vehicle spends at the toll station

Unit: seconds

Toll collection type	ETC	Small vehicle		Big vehicle	
		By ticket	By cash	By ticket	By cash
Time/ Vehicle	0	0.26	3.4	0.3	8.4

- Present layout of the Yangmei toll station: (see Figure 7)

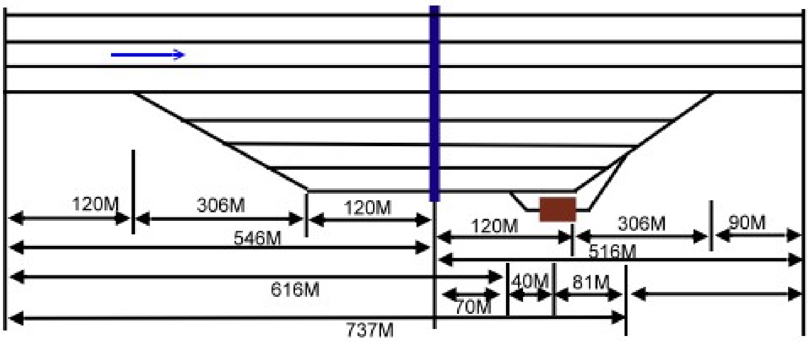

Figure 7 – Present Layout of the Yangmei Toll Station

The TPS simulation results are summarized as Figure 8 and Table 5. The "2-1" means 2 small vehicle ETC gates and 1 big vehicle ETC gate installation in all 8 tollgates. Figure 8 shows vehicle speed increases with the ETC percentage increases. However, the effectiveness is different with different ETC percentage in different ETC gate layouts. It will get more effectiveness when we set much more big vehicle ETC gates in high ETC usage percentage.

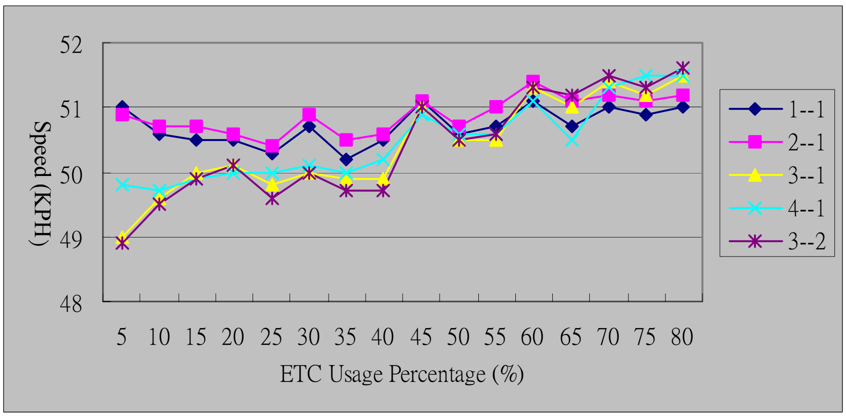

Figure 8 – Average Vehicle Speed with Different Layouts of ETC

Table 5 shows the delay condition of heavy vehicles after passing through tollgates before entering the weigh station.

Table 5 – Delay time of heavy vehicle after passing through tollgates before entering the weigh station

Unit: seconds / vehicle

Use ETC %	Layout of ETC				
	1--1	2--1	3--1	4--1	3--2
5	3.24	3.34	4.81	3.24	4.81
10	4.53	4.53	6.2	4.53	4.63
15	4.55	4.55	6.21	4.55	4.65
20	3.15	3.15	3.15	3.15	3.15
25	4.8	4.6	4.6	4.6	4.6
30	4.86	4.6	4.6	4.6	4.5
35	6.32	6.16	6.16	6.16	6.16
40	6.3	6.14	7.55	7.55	7.63
45	3.29	3.29	3.06	3.06	3.06
50	7.31	7.13	7.01	7.01	7
55	4.78	4.78	4.55	4.55	4.55
60	6.21	6.21	4.53	4.53	4.53
65	4.88	4.88	4.62	4.62	3.13
70	2.98	3.24	2.98	4.54	3.14
75	3.01	3.98	3.14	3.85	4.79
80	4.35	4.61	4.35	6.17	4.61

The time saving of the ETC and ES integrated system could be calculated by following equations:

(1) Non-overweight heavy vehicles equipped with OBU
vehicles × percentage of heavy vehicles × percentage of non-overweight heavy vehicles × OBU usage percentage × (traditional toll collection time + delay time of heavy vehicle after passing through tollgates before entering the weigh station + average weighing time of each heavy vehicle)
(2) Overweight heavy vehicles equipped with OBU
vehicles × percentage of heavy vehicles × percentage of overweight heavy vehicles × OBU usage percentage × traditional toll collection time

By comparing the overweight vehicles percentage analysis algorithm and the TPS simulator simulation, the TPS simulator can analyze much more different conditions of ETC and ES integration.

4.2 Traffic Conflict Volume Reduction Benefit Analysis

In the traffic conflict volume analysis, we need the lane utilization of each vehicle type firstly. According to the data collected at 07:00~09:00, 8 September 2003, the lane utilization is summarized as Table 6.

Table 6 – Lane utilization of each vehicle type

	Small vehicles			Bus			Truck, Tractor-trailer		
	Outer Lane	Medium Lane	Inner Lane	Outer Lane	Medium Lane	Inner Lane	Outer Lane	Medium Lane	Inner Lane
Volume (vehicles /2 hours)	965	2484	2551	0	0	0	0	0	0
Percentage	0.16	0.41	0.43	0.82	0.18	0	0.95	0.05	0

The traffic conflict equation is E(TC)=NX, where N, X are two crossing or merging traffic (Lin et al., 1999). The traffic volume is assumed as: small vehicle: 5530 vehicles/2hours, bus: 420 vehicles/2hours, truck and tractor-trailer: 1050 vehicles/2hours. We can also calculate the lane volume of each vehicle type by Table 6. In the condition of the percentage of overweight heavy vehicles is 4.633%, the traffic conflict volume analysis results by different percentage of heavy vehicles equipped with OBU are summarized as Table 7.

Table 7 – The traffic conflict volume by different percentage of heavy vehicles equipped with OBU

Unit: vehicles^2/2 hours

OBU usage percentage	Heavy vehicle conflict volume		OBU usage percentage	Heavy vehicle conflict volume	
	Overweight	Non-overweight		Overweight	Non-overweight
5	5547	106859	55	5547	50618
10	5547	101235	60	5547	44993
15	5547	95611	65	5547	39369
20	5547	89987	70	5547	33745
25	5547	84363	75	5547	28121
30	5547	78738	80	5547	22497
35	5547	73114	85	5547	16873
40	5547	67490	90	5547	11248
45	5547	61866	95	5547	5624
50	5547	56242	100	5547	0

5. Conclusions

It is known that WIM does not have the same accuracy as static weigh scales. Therefore, the static weigh system is the major device used directly for enforcement in Taiwan. In order to improve the efficiency of static weigh systems on freeway, the Taiwan Area National Expressway Engineering Bureau has developed some WIM systems to sort potentially overweight heavy vehicles from vehicles that are not likely to be overweight. The heavy vehicles that are selected by the WIM need to be weighed statically. The WIM system used to sort potentially overweight heavy vehicles is also called the screening system in functional categories of WIM system. In the present screening system configuration, it is usually difficult to signal to individual trucks by traditional signals installed at the roadside. The Electronic Screening (ES) is therefore developed to improve some disadvantages of traditional signals by utilizing the Automatic Vehicle Identification (AVI) system. The AVI is also a major subsystem of the Electronic Toll Collection (ETC) system in the Intelligent Transportation System (ITS). With the same AVI technology of ETC and ES, these two systems could be integrated to achieve "shared software/hardware items, multiple functions" effectiveness. The feasibility test of the integrated system of ETC and ES has also been implemented in Taiwan.

Besides, it is also necessary to integrate ETC and ES on the freeway systems in Taiwan due to the special layouts of toll collection plazas and weigh stations. The weigh stations are installed at the near upstream or downstream of toll collection plazas on the freeway systems. Since the distance between the weigh station and the toll plaza is short, commercial vehicles still have to enter the roadside static weigh station immediately before or after passing the ETC plaza. Not only the travel time couldn't be saved effectively but also the weaving conflicts will be increased while commercial vehicles change lanes to enter the roadside static weigh station. This study develops a performance model with time saving analysis and conflict volume reduction analysis and illustrates the model applications through the case study. Some results from this study could provide useful evaluation basis for future ETC and ES deployments in Taiwan.

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SUMMARY OF SESSION 3 : WIM DATA QUALITY, APPLICATION TO TRAFFIC MANAGEMENT AND ROAD SAFETY

Head of Traffic Monitoring, Road Operation, Signs and Lighting Department at LCPC. Chair of COST 323 (WIM), co-ordinator of WAVE project, Chair and vice-chair of Scientific Committees of 1st, 2nd and 3rd WIM conferences.

Chris Koniditsiotis is the National Manager of the Austroads Intelligent Access Program. Chris has been involved in WIM for over 17 years & is a member of the ICWIM Scientific Committee. He has Bachelor and Master degrees in Engineering

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This session contained seven formal presentations, covering three broad areas.

1. The use of WIM in traffic and environmental management (Poulikakos, Lily, K. Heutschi, P. Anderegg, R. Calderara, E. Doupal, R. Siegrist and MN Partl – *Determination of the Environmental Footprint of Freight Vehicles,* Calderara, R. D. Barz and E. Doupal – *Advanced System Solutions for New WIM Applications*),
2. The use and integration of WIM within electronic toll collection (Yi-Hsien Chen, and Chou, Chia-pei *Planning and Testing of Integrated System of Electronic Toll Collection and Weigh-in-Motion on Freeway* – Chang, Chien-Yen Yun-Ling Liang and Yun-Ling Chang – *Development of Integrated Performance Model for Integrated System of Electronic Toll Collection and Electronic Screening on Freeway*),
3. Improvements in vehicle classification and site validation through WIM (Maeder, Claude & Humer, Don – *Statistical Analysis of Data to Estimate the Trend of WIM Systems* – Ostrom, Barbara K., GJR Rada, and RW Plett – *Validation of a WIM Smoothness Index Derived from Profiles Collected by Inertial Profilers).*

In benchmarking the content of these papers to the similar session held at the previous ICWIM3 conference in 2002 it can clearly be seen that the application and integration of WIM across other traffic management systems has progressed significantly. In particular, WIM is very much a mainstream component of a total traffic management solution. Additionally, and very importantly, is now being considered as part of the tolling or pricing solution. Furthermore progress is being made in the use of WIM to ensure better and improved quality of data.

The broad subject matter of this session stimulated a number of questions and discussion. Summary of this discussion is presented herewith for each of the three broad areas covered.

1. Use of WIM in Traffic and Environment Management.

The eight sensor array WIM used in Japan and described in the paper '*Advanced System Solutions for new WIM Applications*' triggered significant discussion. Bernard Jacob (LCPC) asked a series of questions dealing with the configuration of the multi-sensor array. It was recognised that the particular site chosen for the WIM installation comprised a varying speed range from 10 to 80km/h and as such different sensors were used for different speed ranges. Thus not all eight sensors were used at a single time, rather depending on the speed of the vehicle one set was used. This highlights the maturing of WIM to accommodate different traffic speed scenarios within the same location.

The paper *'Determination of the Environmental Footprint of Freight Vehicles'* whilst describing research which is still under development raised a number of discussion points dealing with the criteria for vehicular vibration movement (ie. mounting and location of the vibration censors). This work opens a completely new regime for WIM as part of an integration with other both standard and developing capabilities.

2. Use and Integration of WIM within Electronic Toll Collection

The two papers dealing with this issue described the planning and testing and associated development of an integrated system for electronic toll collection and WIM on a freeway. It was identified that currently in Taiwan charging is based on the type of vehicle (ie. car, bus or truck). The speakers were asked if the intention is to move (via WIM) to a mass distance charge for the freeway network, the speakers responded that this was not the intention. Rather, to ensure mass loading compliance via the integration of high speed WIM with checking stations along the freeway corridor. It was noted that the integration of WIM within the freeway system and in particular electronic toll collection (for vehicular identification purposes) was critical for Taiwan. During the discussion reference was made to a South African approach which charged based on vehicular mass on the use of a specific tunnel within South Africa. It was reported that this approach that was initially planned, however had not been implemented due to issues in dealing with cash and its transfer on site. This highlights the issue of integration and holistic systems approach to development of initiatives. In this case it is clear that the 'weakest link' was the handling of payment and its associated difficulties.

3. Improvements in Vehicle Classification and Site Validation Through WIM

The presentation '*Vehicle Classification – a New Approach*' stimulated significant discussion amongst the attendees. Whilst initially not clear, explanation was offered on the algorithm used to distinguish unclassified vehicles. The approach was based on effectively a 'cost value' which indirectly measured the effort required to adjust axles versus that of adjusting the entire vehicle. Questions, were asked on the use or otherwise of the individual axle loads (which are also collected). Chris Koniditsiotis (Austroads) stated that this new approach and the future inclusion of mass as a determiner was not simply a classification system (number and spacing of axles), rather a vehicle identification system (number of axles, spacing and mass) and is particularly useful in environments in which the same vehicular footprint exists but the vehicle is substantially different from functionality (example, a tanker truck versus a bus). As such, this new approach should be regarded as not simply classification but also identification.

Chris Koniditsiotis also went on to say that it is normal practice for the vehicular fleet of a region or a country to change and evolve over time. Vehicle classification system is simply a quantification of that vehicle fleet from time to time. In Australia and other countries on an ongoing basis the vehicular classification system is assessed to ensure consistency and upkeep with the country's vehicular fleet. The approach identified in the paper provides a means to achieve this on a ongoing basis via the use of WIM.

Rolland Henny (DWW) stated that this classification was very much a new approach providing new opportunities. Victor Dolcemascolo (LCPC) enquired about the algorithm associated with the classification approach.

Eugene O'Brien (UCD) enquired about the use of the International Roughness Index (IRI) as the measure of WIM smoothness with respect to the paper '*Validation of WIM Smoothness Index Derived from Profiles Collected by Inertial Profilers*' The author stated that IRI is not used because it does not reflect very well the actual heavy vehicle (ie. truck) response. Rather an index has been adopted that is more appropriate for truck dynamics.

This session demonstrated that overall WIM has become an enabler in providing increased capability to the traffic systems. This is being demonstrated in the routine use and adaptation of WIM in areas that only a few years ago were not considered feasible. Additionally in the movement to integrate and better use WIM for purposes that only a few years ago were not considered.

SESSION 4 :

USE OF WIM DATA AS A TOOL FOR ENFORCEMENT

Chairperson: Chia-Pei Chou
Co-chair: Hans van Loo

REMOVE, REQUIREMENTS FOR ENFORCEMENT OF OVERLOADED VEHICLES IN EUROPE

A graduate in Electrical Engineering from the University of Twente, he joined the Traffic and Transport Division of the National Police Agency as a technology advisor in 1994. Since 1999 he is project manager of the WIM-Hand project at the Road and Hydraulic Engineering Division (DWW) of the Dutch Ministry of Transport, Public Works and Water Management. The DWW is a partner in the REMOVE project.

Bsc Civil Engineering. Worked as research assistant at the Road and Railroad Lab. of the TU-Delft. Since 1991 at the Road and Hydrauilc Engineering Institute as projectmanager and since 1999 as head of the Pavement Loading and Winter Maintenance group. Mr. Henny is responsible for the development and implementation of WIM-systems at the Dutch motorways. Member of the Scientific Committees of all IC-WIM conferences.

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Abstract

Road transport of goods by overloaded trucks creates a number of serious problems on Europe's road network, such as unfair competition, less safety, less mobility and considerable extra costs for additional maintenance/repair infrastructure (pavements and bridges). After finishing prior EU projects which mainly focussed on the technological part of WIM, it was recognized, that these projects needed a follow up, focussing more on the implementation WIM-technology in overload enforcement strategies within the EU. That is why the REMOVE project was initiated. The name 'REMOVE' stands for Requirements for EnforceMent of Overloaded Vehicles in Europe. The proposal for the REMOVE project is submitted to DGTREN as part of the Call for Proposals for a Grand Application Transport 2003. The project has officially started in April 2004.

Key words: Application, Enforcement, Overloading, Requirements, Weigh-in-Motion.

Résumé

Les transports routiers en surcharge créent de sérieux problèmes au réseau routier européen, distordent la concurrence, réduisent la sécurité et la mobilité et induisent des coûts additionnels considérables de maintenance et réparation d'infrastructure (chaussées et ponts). Après l'achèvement de projets européens principalement concentrés sur les aspects techniques du pesage en marche, il a semblé utile de poursuivre sur les stratégies de déploiement de ces techniques pour le contrôle des surcharges dans l'union européenne. C'est l'objectif du projet REMOVE (Besoins en matière de contrôle des véhicules en surcharge en Europe). Ce projet a été soumis à l'appel à propositions de la DG/TREN pour une aide Transports 2003. Le projet a officiellement démarré en avril 2004.

Mots-clés: Pesage en Marche, Contrôle, Surcharge, Besoins, Application.

歐洲超載車輛執法規定

摘要：

重車超載對歐洲的公路路網造成許多嚴重的問題，如不公平競爭、安全性降低、機動性減少及對基礎設施如鋪面及橋樑造成龐大的額外維修成本等。在結束歐盟之動態地磅(Weigh-in-Motion, WIM) 前期技術研究計畫後，需要更進一步針對動態地磅於超載執法策略之應用進行探討。因上述原因，REMOVE 計畫因應而生。 REMOVE (Requirements for EnforceMent of Overloaded Vehicles in Europe) 全名代表歐洲超載車輛執法需求。REMOVE 計畫之提案已在 2003 年提送至 DGTRENM 並為大型運輸應用 (Grand Application Transport) 徵求計畫構想書的一部分。此計畫於 2004 年的四月正式開始。

關鍵字：應用、執法、超載、規定、動態地磅

1. Introduction

After finishing previous EU projects (COST-323, 2002; WAVE, 2001; TOP TRIAL, 2002) under several Framework Programmes, that had mainly been focusing on the technological side of Weigh-in-Motion, it was recognised by the public authorities, that these projects needed a follow up, focussing less on technology and more on the issue of implementing WIM-technology in a more or less harmonised way within enforcement strategies in the EU. It was noticed that there are big differences in the field of deploying WIM-technology in the various EU member states. Even for 'traditional' enforcement of overloading, the types of systems used and enforcement operating practices are based on different legal systems.

From the point of view of the transport industry this is totally unacceptable. It seems there is a lack of principles of fair competition and of equal treatment and proportionality. With the extension of the EU by numerous member states in 2004 it is expected that a considerable number of member states will start implementing Weigh-in-Motion systems during the next years to come (some have already started to do so). Activities to realise a more or less harmonised approach within the EU have to be started on short notice. This requires a strategic approach to the use of WIM technology, primarily on the TERN (Trans European Road Network) but also across other linking roads within countries.

The applications of WIM for enforcement are, in order of advance:

- use WIM data for statistics and deployment of controls at the right time and location;
- use WIM as pre-selection tool for controls;
- use WIM data for preventive activities (company inspections based on data);
- Automatic enforcement using WIM-data;

2. Background

2.1 Overloading

Road transport of goods by overloaded trucks creates a number of serious problems on Europe's road network. These include unfair competition, reduced safety, mobility and considerable extra costs for additional maintenance/repair of the roads.

1. <u>Unfair competition</u>. Overloading creates an illegal and unfair advantage for some operators allowing them to charge lower prices for the same journey; this has a negative effect on price levels. This phenomenon then causes non compliance in all kinds of other areas, because bona fide transport companies cannot compete anymore with companies that operate illegally on lower prices levels, because they overload their trucks;
2. <u>Safety</u>. It is clear, that overloaded trucks pose an extra risk to safety, because in emergency situations the braking distance is longer. But there are more safety risks. Trucks that are extremely overloaded (and therefore slow) often urge drivers of cars to make dangerous overtaking manoeuvres on secondary roads. Overloaded and incorrect loaded trucks have reduced handling capabilities which can result in veering from lanes and, in extreme cases even resulting in a higher risk of toppling over;
3. <u>Extra maintenance costs</u>. Overloading the total permitted weight generally results in the accelerated aging of structures such as bridges, viaducts and the substructure of roads.

Overloading of various axles generally results in an accelerated ageing of the road surface. This is demonstrated in rutting, fretting or holes in the road. Due to the different power-laws for the various sorts of road-damage it is clear that overloaded axles cause a considerable part of the maintenance costs. Studies in The Netherlands show that overloading is responsible for 17% of the maintenance costs for the main road network. Although there is not enough information about the secondary road network, it is assumed that damage to the secondary road network is probably even more. The more frequent than necessary repair works that have to take place in order to restore the roads poses extra safety risks for road users and road workers. As repair works on motorways have to be carried out more frequently there is a negative effect on mobility and life cycle costs. Furthermore rutting caused by trucks is directly related to safety, it not only creates manoeuvring difficulties for vehicles that enter them, it also causes dangerous situations for cars (and trucks), especially in rainy and icy weather conditions (splash and spray).

As road transport by trucks increases these problems become more and more severe. The problem of overloading in the domain of road truck transport is mainly caused by deliberate non-compliance by the road transport industry to the rules regarding maximum axle loads and total vehicle mass of trucks. Mostly the transport companies can be held responsible for this non-compliance behaviour. However in a number of cases the transport industry do so unintentionally e.g. when part of the load of a truck is removed which may result in overloading of an axle due to the now unequal distribution of weight on the vehicle.

2.2 Enforcement

Providing effective, efficient and fair enforcement of axle loads and vehicle masses, to ensure that there is an adequate deterrent is not an easy task. The traditional way of checking on overloading by the police or by traffic inspectorates requires the vehicle to stop in order to guide it over a fixed or mobile road side weigh system. The number of trucks that can be controlled using these methods is only a fraction of the total number of trucks on the roads and requires a lot of staff. The chance of being caught when exceeding maximum axle loads and/or vehicle masses is very small, and the selection of vehicles is inefficient. The number of trucks that are operated is simply far too big to create an acceptable level of control, using the traditional methods. Furthermore a lot of non-overloaded trucks are selected for control, causing undesirable delay for transport companies that respect the rules and thus, unnecessary costs and waste of resources to the community as a whole.

Therefore a new type of enforcement was developed, based on the use of WIM technology, combined with technology that identifies the vehicle automatically. Weigh-in-motion offers the potential to the enforcement agencies to enlarge the number of checks on trucks drastically. At the same time it enables free flow for non overloaded vehicles. In some of the EU member states a considerable expertise about using WIM in enforcement strategies is already available, where semi automatic devices are used as a screening tool for pre selection of overloaded vehicles. However the most effective technology available today, still requires significant development before a truly reliable and automated functionality can be delivered. These developments in technology will in the end undoubtedly lead to systems that are accurate and reliable enough to provide legal evidence for enforcement of overloading of trucks.

3. The REMOVE Project

3.1 General Information

The name 'REMOVE' stands for Requirements for EnforceMent of Overloaded Vehicles in Europe. The proposal for the REMOVE project has been submitted to DGTREN as part of the Call for Proposals for a Grand Application Transport 2003. The proposal has been accepted and the REMOVE project has officially started in April 2004. The total costs for the REMOVE project are Euro 450.000,--. The total work is done in 66 man months within the duration of the project of 24 months. During the project three general workshops will be organised to exchange the results so far and to coordinate the actions in the coming period. Also a number of special meetings will be organised on topics (e.g. applications and acceptance) which require input from two or more work packages to coordinate the activities that are carried out under the four work packages.

3.2 The Partners

The consortium of partners for the REMOVE project is a unique one, because of the commitment of ECR and TISPOL which represents a vast part of the European "Enforcement Community". TISPOL is the European network of traffic police forces with 16 members, 4 candidate members and 2 members from outside the EU. ECR is the European organisation of traffic inspectorates with 8 members. In their council meetings all members of ECR and TISPOL supported participation in this project. The enforcement bodies that were chosen to represent ECR and TISPOL can really speak on behalf of these organisations. This creates an unusually wide basis for consultation and expertise and will lead to support for the findings of this project. Also unique is that the transport industry, the ministries of transport and the enforcement agencies will co-operate in this project in order to develop new ways of enforcement that are acceptable for both sides (industry and enforcement agencies) as well as to discuss more structural solutions to solve the problem of overloading in future. The International Road Transport Union (IRU) therefore will fulfil a very important role in this project.

The participation of the Ministries of Transport of Germany, France and The Netherlands will guarantee good coverage of the ministerial know-how and experience regarding WIM technologies that is available in Europe at the moment. Expertise from the Czech Technical University of Prague, some individual WIM experts and Arcadis will complete the level of qualifications, required to conclude the REMOVE project successfully. This project consortium has the skills, expertise and representation to provide recommendations to the Commission on how this strategic and coordinated approach can be achieved. The findings and recommendations of this project could be the basis for an EU-directive regarding fair, efficient and effective enforcement of overloading in the EU.

4. Project Break Down

General objective of the REMOVE project is to present to the European Commission the requirements (strategical, tactical, legal technical, operational) for the harmonised and interoperable deployment of Weigh-in-Motion systems in the enforcement of overloading throughout the EU. The REMOVE project consists of five work packages that are closely related. The overall picture of the project is shown in Figure 1.

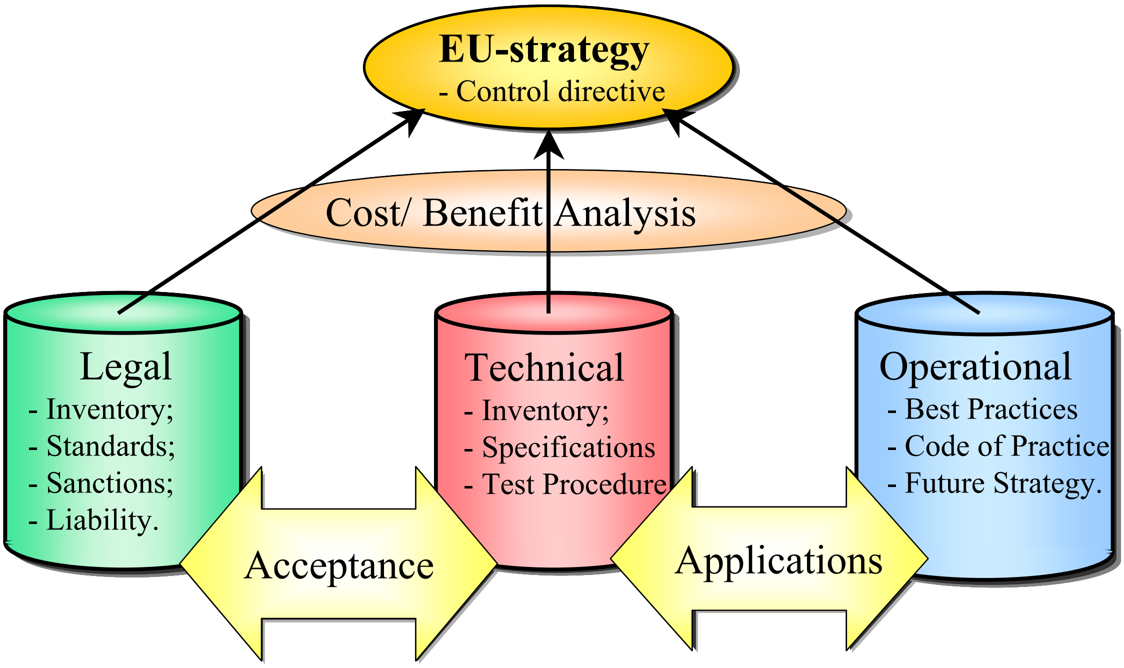

Figure 1 - Overview of the REMOVE Project

4.1 Legal Issues

In the "Legal Issues Work Package" recommendations will be developed that focus on providing a solid legal basis for the introduction of Weigh-in-Motion systems. When it comes to developing legal frameworks for new enforcement strategies, based on gathering a lot of information from (semi) automated road-side systems and using this information to provide "compliance profiles" of companies, this project will have a clear relationship with other projects like VERA II (2004) (Video Enforcement Road Authorities) and EVI (Electronic Vehicle Identification), for protocols on data exchange, data handling and the managing of cross border penalty enforcement. Under this work package the following products will be delivered:

1. Inventory of the present situation within EU. An overview of the situation in the various EU member states regarding legal acceptance of the use of axle/vehicle weighing equipment and an overview of the available WIM technology;
2. Required standards for legal acceptance. Defining and describing the various elements that are needed from a legal point of view to establish enforcement legislation. The legal framework, required for implementation of Weigh-in-Motion as an enforcement tool on a European level, will be drawn up. In order to create effective cross border enforcement strategies for the future, certain conditions will have to be created at the European level. Conditions like: European type approval for enforcement equipment, standards for the legal exchange of enforcement information between member states, European standards for vehicle identification.
3. Sanctions. An overview will be given of the level of fines and other sanctions as applied at present in the various EU member states. It will consider how the present approach works out for the transport industry as well as for the enforcement agencies. A recommendation will

be made, focussing on improvement of the present situation into a more harmonised and balanced sanction policy in EU-member states;

4. The responsibility and liability for overloading. The relationship between the driver, transport operator and shipper will be considered and recommendations as to which parties sanctions could apply to in given circumstances will be developed. Some EU-member states have created a certain level of legal liability for shippers, in case they deliberately order transport companies to transport too heavy loads.

4.2 Technical Issues

In the "Work Package Technical Issues" technical specifications and procedures for legal acceptance of the different applications of Weigh-In-Motion for enforcement will be defined. The following products will be delivered under this work package:

1. Inventory of WIM technology. An inventory will be made of existing technology and used (legal) technical specification for (high speed) WIM systems for the four enforcement applications mentioned before;
2. Specifications. This product consists of the functional and certain technical specifications for WIM-systems to be used for each of the above mentioned applications. The specifications will be a combination of what is operationally and legally required (input from Work package 1 and 3) and what is technically possible. This will include requirements such as system reliability, system accuracy, the way of processing information, tolerance levels, privacy aspects, integrity of data storage and data transport. Consideration will be given to the development of a data format for the exchange of information on overloaded vehicles between EU-member states;
3. Test Procedure. The establishment of a test protocol, defining and describing the procedures legal acceptance of WIM-systems. This protocol should be both practical and well founded. Practical means that it should be possible to perform the test within operational boundaries, e.g. the number of trucks required for the test. Well founded means that the test procedure should be scientifically well founded to avoid question on the outcome. The test protocol involves the following:
    a. A test-procedure, a description of which tests should be done and how they should be performed. This includes not only the initial (type-) approval test but also the periodic performance tests;
    b. A certification protocol for initial legal approval of WIM-systems. This will have a close link with the ‘required legal framework and standards’ part of work package 1.

4.3. Operational Issues

The "Work Package Operational Issues" is about the exchange of operational (best) experiences between enforcement agencies, in order to benefit from the lessons learned by others and to adopt successful procedures from others. This will lead to more uniform enforcement practises in Europe. The following products will be delivered under this work package:

1. Best practise: An overview will be presented of the existing operational procedures and practises in the EU m.s. Differences in organisational structures, responsibilities and authority of the various enforcement agencies of the EU, involved in enforcement of overloading will also be shown;
2. Code of practice. Based on the findings of the above mentioned "Best-practice" product, recommendations for a so-called ‘Code of practice’ will be defined. In this recommended

Code of practice the best of the existing enforcement practices of the EU member states will be combined into an advised working procedure;

3. Future Enforcement Strategy. A recommendation will be made on how to organise the enforcement of overloading in the future. The various ways in which WIM systems can be deployed will be addressed. Enforcement models, based on new (EU- wide) strategies will be presented. This will have a close link with the applications and specifications part of work package 2.

4.4 Cost/Benefit Analysis.

The "Work Package Cost/Benefit Analysis". A cost benefit analysis is an important tool in the process of building political awareness regarding the advantages of (the use of WIM for) enforcement of overloading The following products will be delivered under this work package:

1. Damage to infrastructure. Based on available information an estimate of the costs of repair of damage to the TERN, due to overloaded trucks will be presented. This will not be a new scientific study; it will be a calculation, based on results of previous research. An estimate of the loss of time/mobility on the TERN because of damage by overloading will be presented.
2. Efficiency of enforcement. A model will be derived to estimate the cost, required to build, maintain and operate WIM-systems for enforcement. The calculations will also include the cost of staff also a comparison will be made with the present enforcement practises.

4.5 Management

The work package "Co-ordination/ Management" will consist of the activities needed to ensure co-ordination between the various project partners and their activities, the progress of the project, the financial control, other relevant support to the project partners and reporting to the European Commission.

5. Results and Conclusions

5.1 Results

Because all workpackages start with an activity inventory (or best practice) it was decided to combine all questions in one questionaire. This way the answers to all questions are directly available to all workpackages and more important people only have to answer one set of questions. By the end of 2004 the results from the questionaire will be combined in a report. Since the start of the project in April 2004 a number of meetings has been organised in the different workpackages. The results so far consist of an agreement on the approach of the work to be done and the division of the work over the partners. No final reports or project deliverables are available yet.

5.2 Conclusions

- A grand application project named ‘REMOVE’ has started in April 2004;
- Objective of the project is to present requirements for the harmonised and interoperable deployment of WIM-systems in the enforcement of overloading throughout the EU;
- The project partners consist of enforcement agencies (Tispol and ECR), Road Authorities, Transport industry and WIM-specialists;
- In the project the <u>applications</u> of WIM for enforcement are leading.

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OVERLOADED VEHICLES SCREENING

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Abstract:
Since 2001, the Ground Transportation Division of the French Ministry of Infrastructure and Transportation has experimented with two weigh-in-motion systems, associated with video and automatic vehicle plate recognition, in order to screen vehicles that are suspected to be overloaded or overspeeding. This paper describes the systems and their effectiveness, as well as some technical problems encountered during the two operating years. Thanks to this test and since the beginning of 2004, the Ground Transportation Division decided to equip the French road network with 10 similar systems. Future network structure is presented.

Keywords: Weigh-in-Motion, Preselection, Screening, Overload, Video, VIDEO-WIM.

Résumé :
Depuis 2001, la Direction des Transports Terrestres (DTT) du ministère de l'Equipement et des Transports français expérimente deux systèmes de pesage en marche associés à la prise d'image vidéo et à la lecture automatique des numéros d'immatriculation, afin de présélectionner les véhicules supposés en surcharge ou en dépassement de vitesse. Cet article présente les systèmes et leur efficacité, ainsi que certains problèmes techniques rencontrés durant ces deux années d'exploitation. Suite à cette expérimentation et depuis le début de l'année 2004, la DTT a décidé d'équiper le réseau routier français de 10 systèmes similaires. L'architecture du futur réseau sera présenté.

Mots-clés: Pesage en Marche, Présélection, Surcharge, Vidéo, VIDEO-WIM.

超載車輛之篩選

摘要：
自 2001 年起，隸屬法國基礎建設與運輸部之陸地運輸局針對兩套動態地磅 (Weigh-in-Motion, WIM)系統進行試驗，這兩套系統主要是利用影像與自動車輛辨識技術來篩選可能超載或超速的車輛。此篇論文針對上述系統及其有效性進行說明，並探討在兩年運作其間所遭遇到的技術問題。基於上述之成功測試，自 2004 年起陸地運輸局決定在法國路網中裝設十套類似的系統。未來的路網結構亦在本文中一併說明。

關鍵字：動態地磅、預選、篩選、超載、影像、動態地磅影像

1. Introduction

In 2001, the *Ground Transportation Division* of the *French Department of Equipment and Transportation* funded the implementation of two VIDEO-WIM systems, allowing to detect overloaded vehicles, i.e. axle loads or gross weights above the legal limits, to take video pictures of them, and read automatically the vehicles plates. Final objective of these systems is aimed at automatic enforcement. As an intermediate step, improvement of enforcement effectiveness, on site or in transport companies is aimed, using results of these VIDEO-WIM systems according to the following process:

- A picture per vehicle measured as overloaded or overspeeding by the WIM sensors is immediately transmitted (by means of radio waves or telephone network) to the transport inspectors or police officers standing on a static weighing area. Those vehicles, which will be named hereafter as 'screened vehicles', once identified, are stopped and statically weighed. Vehicles which are finally found overloaded are fined.
- Records of pictures over several days of measurements lead to identification of transport companies often committing offences. Enforcement within the companies can then be organised.
- Records of data allow to identify the hours of the day, days of the week or days of month statistically providing the most important amount of supposed overloaded vehicles. This data can be used to suit the weighing strategy to the most 'overloaded' periods.

The two systems were installed on roads with heavy traffic, and were already presented in (Maeder & Stanczyk, 2002), but many improvements were implemented by the manufacturers. This paper proposes a presentation of the future VIDEO-WIM French network structure, a description of the tested systems and their effectiveness.

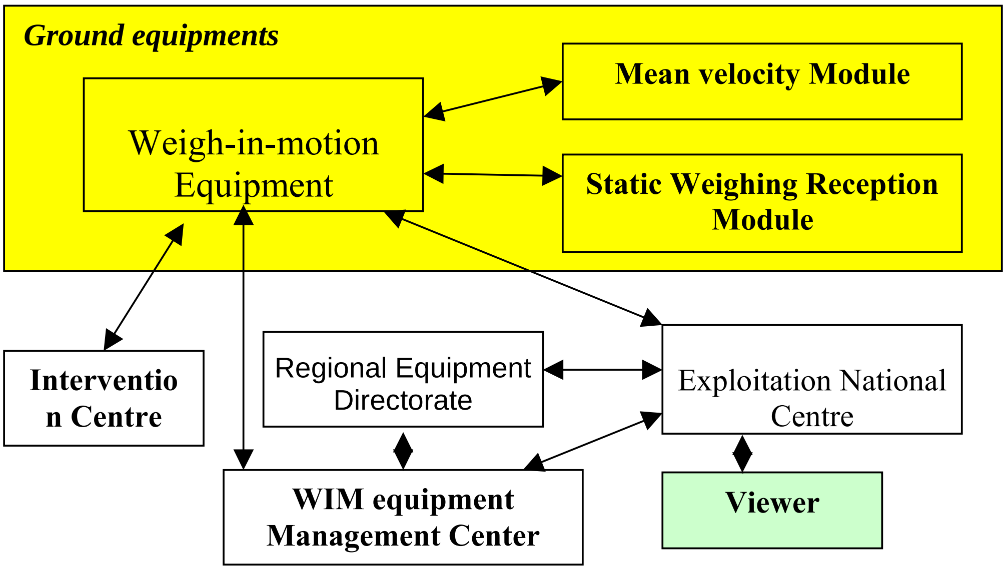

Figure 1 - General Weighing Network Structure Diagram

2. Weighing Network Structure

In June 2004, future network architecture was defined (Figure 1). It will be composed of 3 distinct ground equipments, and 4 management entities, as described hereafter.

2.1 Ground Equipment

The ground equipment includes 3 distinct modules (Figure 2):

- The WIM Module (WIMM), which measures axles and gross vehicles weights, vehicles speed, and identifies heavy vehicles type (silhouette). The WIM module also allows overloaded or overspeeding vehicle picture capture and identification (registration plate reading). Pictures and data are stored and aggregated in files.
- The Mean Velocity Module (MVM), which is located at a precise distance from the WIMMM on the same itinerary. It calculates the vehicle's mean velocity by recording the time between the WIMM and the MVM, knowing the distance. Used technology is not yet defined (camera, inductive loop,…).
- The Static Weighing Reception Module (SWRM), which is located downstream from the WIMM, on the parking area where the static weighing is carried out. It allows real time visualisation of screened vehicles.

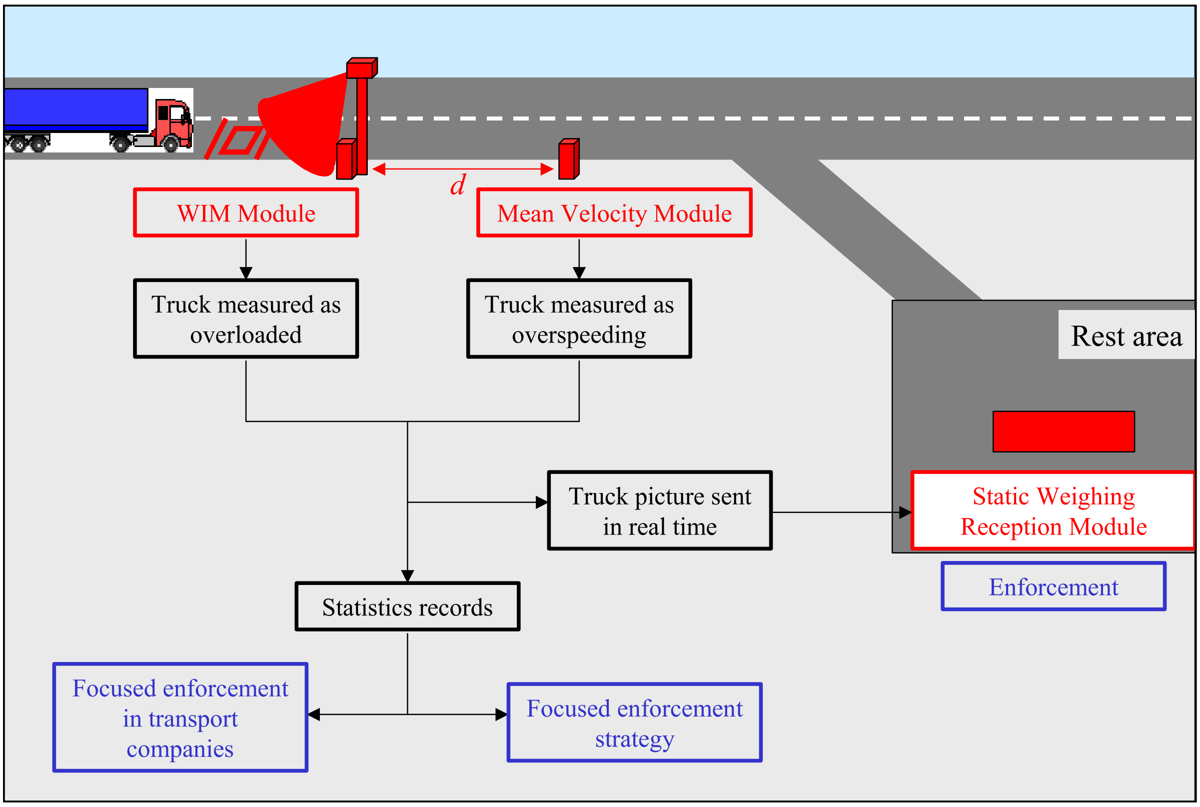

Figure 2 - Ground Equipment Diagram

2.2 Management network

The weighing network management will be organised into 4 entities:

- The Exploitation National Centre (ENC) receives the screened vehicles pictures and data from all WIMM. The ENC will use the registration plates to identify which companies to enforce, and send the companies identitied to the Regional Equipment Directorate.
- The WIM management centre controls the WIMM and carries out statistics.
- The Regional Equipment Directorate carries out on site enforcement with the SWRM and the MVM, and enforce the screened transport companies.
- The Intervention Centre is located downstream from WIMM and will receive the pictures and data of vehicles with high overloading in order to intercept and enforce them.

3. Tested WIMM Description

Two WIMM were installed in Eastern France by the manufacturers Electronique Contrôle Mesure and STERELA on roads with heavy traffic. The first site is located at GUEMAR on national road 83 in the south-north direction, while the second is located on highway 31 in the North-South direction. Only one lane was equipped with piezoceramic sensors. The WIMM is composed of various sub-modules:

- Vehicle detection and axles and gross weigh measurement with 2 piézoceramic bars and an electromagnetic loop on each lane,
- Monochromic high definition video, associated with a registration plate recognition software (60 % of identified vehicles at least), in order to carry out focused and on site enforcement of screened transport companies. The camera is placed in a box ensuring temperature stability,
- Local processing unit, which controls the various peripheral modules, and carries out data processing, and the storage of data files and more than 10000 pictures,
- Storage module, in which the memorised data are copied.
- Communication module to transmit data.

To limit the vandalism risks, the electronic devices are protected by a metal cabinet, installed in a concrete shelter with a metal door.

To facilitate data analysis by the central entities, data files structures and formats were defined as:

- Light and heavy vehicle flow per hour,
- Overloaded vehicles flow per hour, to identify the hours and the days presenting the highest frequency of overloading and define the weight enforcement strategy.
- Heavy vehicles individual data, including the type of suspected enforcement, axle weights, gross weight, speed, date, distance between axles. These data are associated with a picture in case of suspected law violation.
- Aggregate of various data : speeds, loads etc... for the 22 categories of vehicles defined by the Ground Transportation Division, allowing calculation of damage induced by each vehicle category will be possible.

3.1 E.C.M System

The weighing equipment of Electronique Contrôle Mesure manufacturer is approximately located 6 km away from the static weighing area. As shown on Figure 3, the initial detection module is composed of 2 piézoceramic sensors, an electromagnetic loop, and a “Onscale” sensor which allows the measurement validation. The transmission module is composed of a radio transmitter/receiver, allowing to send an image within 2 seconds to the static weighing area, and a telephone modem for the data transmission. The module " Local Processing Unit" is an industrial computer (Figure 4).

A real time plate recognition software was added in 2004. Identification of more than 50 % of the screened heavy vehicles was achieved.

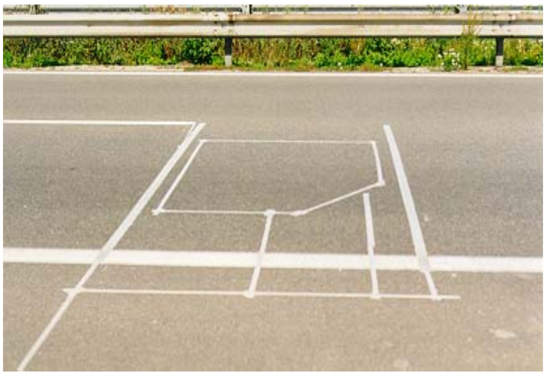

Figure 3 - Piezoceramic Sensors

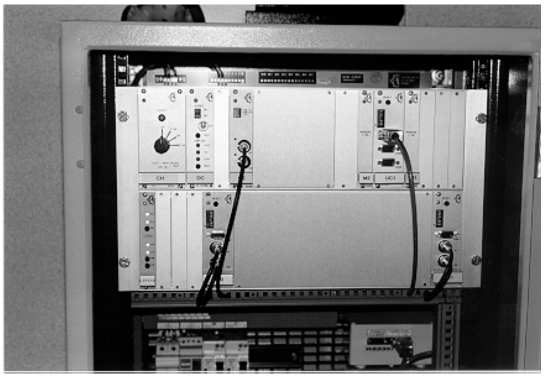

Figure 4 - Industrial Computer

3.2 STERELA System

In October 2003, a new detection module “UD890” was installed. It allows now the weighing with 2 piézoceramic bars as well as the vehicle detection with an electromagnetic loop. A new camera will be installed in a reinforced cabinet above the concrete shelter at the end of August 2004.

4. WIMM Accuracy

4.1 ECM System Accuracy

With the initial system configuration, 77 trucks were weighed in motion with a static reference. Accuracy class according to European WIM specifications (COST 323, 2002) was calculated (Cf. Table1). Gross weight, axles of group and single axles criteria achieved class C(15), but groups of axles only achieved class D+(20). The mean relative error for the gross weight estimation is 3.51 %.

Different bias are observed for single axles and group of axle. Indeed, groups of axles and axles of group are 8% overestimated while single axles are approximately 3 % underestimated. Signal processing carried out by ECM might not be adapted to the road structure of this site.

The sensors were replaced in August 2003, but obtained results were not considered as satisfying. We think that these results are related to a bad quality of the structure of the road. The road structure poor quality is suspected to be responsible for these disappointing results. Deflection will be measured all along the sensor, and, according to the results, a new coating might cover the road, and sensors might be replaced again.

Table 1 - ECM accuracy in (III-R2) conditions according to COST323 specifications

Sensor 1+2	**Number**	**Mean**	**Std. dev.**	π_o	**Class**	δ	δ_{min}	π	**Accepted**
Criteria		(%)	(%)	(%)		(%)	(%)	(%)	**Class**
Single Axles	154	-2.56	9.31	90.3	C(15)	20	17.61	94.3	**D+(20)**
Axles of group	214	8.58	10.28	90.8	C(15)	25	23.78	92.6	
Group of axles	73	8.49	7.20	88.7	D+(20)	23	18.97	96.0	
Gross Weight	77	3.51	5.54	88.8	C(15)	15	11.78	96.5	

4.2 STERELA System Accuracy

Only 2 days of measurement were carried out with the new electronic part of the system. 6 trucks were weighed in motion with a static reference. Accuracy was calculated although the sample is too small.

Global accuracy obtained in D+(20) class. Axles of group criteria reaches B(10) class, while single axles and group of axles reach C(15). Gross vehicles weight only reach D+(20).

Table 2 - STERELA Accuracy in (I-R2) Conditions According to COST323 Specifications

Sensor 1+2	**Number**	**Mean**	**Std. dev.**	π_o	**Class**	δ	δ_{min}	π	**Accepted**
Criteria		(%)	(%)	(%)		(%)	(%)	(%)	**Class**
Single Axles	12	-3.27	7.81	76	C(15)	16	15.5	78	**D+(20)**
Axles of group	18	1.98	6.15	81	B(10)	16	11.9	94	
Group of axles	6	1.98	5.75	56	C(15)	14.4	11.1	78	
Gross Weight	6	-0.47	7.81	56	D+(20)	16	14.7	64	

5. Statistics

The various recorded data files provide results on classified flows, speeds, loads and overloads. Figure 5 presents as an example the heavy vehicles with more than 4 axles flows distribution, measured on highway 31. 11 % of these vehicles exceed the legal maximum gross weight (40 tons), 2.5 % exceed 44 tons and 1 % exceed 48 tons.

Figure 6 presents the speeds distribution for the same vehicles category. 29% exceed the legal maximum speed (90 km/h) and 0,6 % exceed 100 km/h.

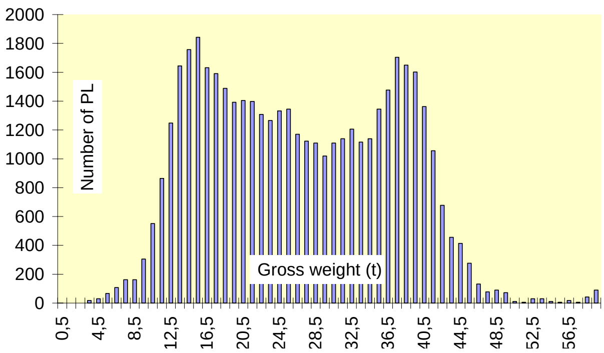

Figure 5 - Gross Weight Distribution

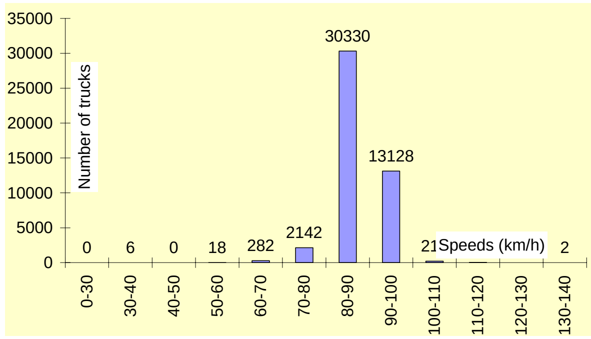

Figure 6 - Speed Distribution

6. Screening strategy

On highway 31, the percentage of enforcing trucks is 3 times higher than the mean percentage on national road network. On the slow lane, 800 trucks per day are overloaded considering a total trucks flow of 3800 trucks per day.

Software "MALOU" provides a statistic summary of traffic data. From this summary, periods with highest frequency of overloading can be identified.

From the Table 3 data (summary provided by "MALOU" software), enforcement will be focused on highway 31 Wednesdays, Tuesday and Mondays between 3pm and 7pm.

Enforcement was usually realised between 9 and 12am, but this table shows that it will be necessary to change the officers usual practices to increase effectiveness.

Table 3 - Traffic Summary on Highway 31

Day	Flow	%	Hours	flow	%
Wednesday	1225	22,7 %	3pm-4pm	54	24,3 %
Tuesday	1208	22,8 %	4pm-5pm	54	23,9 %
Monday	1029	22,8 %	7pm-8pm	52	27,5 %
Friday	863	22,8 %	6pm_7pm	50	26,2 %
Thursday	771	22,9 %	5pm-6pm	49	23,8 %
Saturday	333	22,1 %	8pm-9pm	45	27,9 %
Sunday	131	24,1 %	2pm-3pm	45	22,8 %

7. Enforcement and Vehicles Screening

The two WIM systems are located approximately 10 km away from the areas where the heavy vehicles detected as overloaded are enforced and fined. On these areas, for each vehicle detected as overweighed or overspeeding, a picture of the truck as well as the data measured by the station are sent. Figures 7 and 8 present the respective pictures transmitted by each tested system. For each vehicle, probable hour of arrival on the static weighing area, the various weights of the axles, speed, vehicle type, and other data which could help the enforcement process are indicated.

Figure 7 - E.C.M System Picture

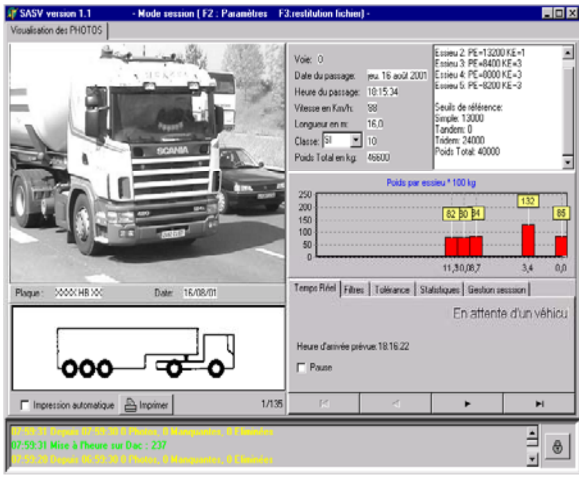

Figure 8 - STERELA System Picture

As shown in table 4, not all the screened trucks are intercepted by the policemen. Only 30 % can be intercepted, because of safety requirements.

Table 4 -Effectiveness Results

		Preselected trucks	**Stopped trucks**	**Overloaded trucks**	**Fined trucks**
RN 83	Total flow	328	104	84	54
	Percentages		32 %	81%	64%
A 31	Total flow	48	12	12	8
	Percentages		25%	100%	67%

60 % of the screened trucks which were also statically weighed were fined because of an overloading rate higher than 5%.

This results is satisfying, as enforcement effectiveness is multiplied by a factor 3, comparing this value to the fining rate without screening.

8. Prevention and Enforcement in Transport Companies

SIREDO-SATL network is composed of 500 traffic and WIM stations distributed on national roads and public highways allowed to estimate that each day, among 16500 recorded trucks, 10% were overweighed.

This rather high rate of overloading, associated to high rate of overspeeding lead the Ground Transportation Division to consider these trucks detection as a priority. Enforcing 5% of the overloaded or overspeeding trucks would allow an important decrease of infractions, assuming that the transport companies would change their behaviour in a sense of a higher respect of the law. This would automatically induce a reduction of the damage caused to the roads and bridges and will an increase of traffic safety. Moreover, it would also allow a fair competition between transport companies and transport modes.

Since May 2004, the WIMM of national road 83 records the registration plates of enforcing trucks. But only 50 % of the registration plates were correctly identified, and there are still problems with the picture caption during the night.

Thus, the manufacturer developed a viewer to validate the registration plates, which was installed in the Regional Equipment Directorate of Alsace in July 2004.

9. Conclusion

Thanks to the screening systems, overloading enforcement effectiveness is clearly improved: less vehicles are stopped and more trucks are fined (60% of the screened trucks).

The system also provides information about the days and the hours with the highest level of overloading, and this will allow to focus the enforcement strategy.

Enforcement effectiveness will significantly improve as soon as the automatic reading of the registration plates will be operational. At this time, none of the two systems reached the required performance.

This experimentation led to imagine a French network of overloading screening. A European call for tender began in September 2004. The first year, 10 equipments will be bought and installed. Afterwards, and depending on the results of the first 10 systems, up to 40 additional systems could be installed within 4 years.

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VEHICLE FOR DYNAMIC CALIBRATION OF A MULTIPLE SENSOR WEIGH-IN-MOTION SYSTEM

A graduate in Electrical Engineering from the University of Twente, he joined the Traffic and Transport Division of the National Police Agency as a technology advisor in 1994. Since 1999 he is project manager of the WIM-Hand project at the Road and Hydraulic Engineering Division (DWW) of the Dutch Ministry of Transport, Public Works and Water Management. The DWW is a partner in the REMOVE project.

Joined Netherlands Measurement Institute, the national standards and metrology body of the Netherlands as a metrological expert and quality consultant.In 1995 he joined Kalibra Int., a commercial calibration and verification company as manager of one of the operational divisions. Through a management buy-out in 1999, in which Mr. Visser participated as one of the shareholders, Kalibra International became independent from NMI. Over the past 5 years Mr. Visser has played an important role in expanding Kalibra activities worldwide

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Abstract
For the Road and Hydraulic Engineering Institute (DWW), an instrumented vehicle has been built. This vehicle will be used for the dynamic calibration of Multiple Sensor Weigh-in-Motion systems It was built by a consortium led by Kalibra International BV with participation of TNO for the measurement technology. The key specifications are: measurinfg axle loads from 5 to 15 tonnes at speeds up to 100 km/h in various axle configurations with an inaccuracy of less than 5%. The synchronisation between the instrumented vehicle and the MS-WIM-system is done by using the exact time signal from GPS receivers. The measuring principle is based on strain gauges and accelerometers.

Keywords: Instrumented Vehicle, Multiple Sensor, Weigh-in-Motion, Dynamic Calibration.

Résumé
Un véhicule instrumenté a été construit pour l'institut technique des routes et d'hydraulique (DWW). Ce véhicule permettra l'étalonnage dynamique des systèmes de pesage en marche multicapteurs et les essais des systèmes à hautes performances nécessaires pour le contrôle. Le véhicule a été réalisé par un consortium conduit par Kalibra International avec la participation du TNO pour la métrologie. Il est constitué d'un tracteur à 3 essieux et d'une remorque à 5 essieux dont un instrumenté. 4 essieux sont directeurs et 4 sont relevables. Le cahier des charges précise que le véhicule doit mesurer les charges d'essieux de 5 à 15 tonnes jusqu'à 100 km/h pour diverses configurations à 5%. La synchronisation entre les mesures embarquées dans le véhicule et celles de capteurs de pesage en chaussée est faite par un signal GPS précis. La mesure de la force d'impact de l'essieu instrumenté est assurée par des jauges de déformation et des accéléromètres qui mesurent l'accélération des roues pour compenser leur mouvements.

Mots-clés: Véhicule Instrumenté, Multicapteur, Pesage en Marche, Étalonnage Dynamique.

應用於複合感測器動態地磅系統之動態校估之車輛設備

摘要：
荷蘭的道路與水利工程研究學院發展出一輛可進行動態校估多重式感測器動態地磅系統之車輛設備。此設備是由 Kalibra International BV 爲主之合作團隊進行研發，於量測技術方面並有 TNO 之參與。其須符合以下規範：不論是何種軸型，其軸重範圍在 5~15 公噸內，於時速 100 公里/小時量測誤差必須小於 5%。此研發之校估車輛與多重式感測器動態地磅系統的一致性，乃利用 GPS 接收器之精確時間訊號達成。本研究之量測原理以應變計及加速度規爲基礎。

關鍵字：裝載設備之車輛、複合感測器、動態地磅、動態校估

1. Introduction

The WIM-Hand project investigates whether existing technology can be used for building an axle load measuring system that can be employed for automatic enforcement of overloading by heavy goods vehicles. Automatic enforcement means that a citation will be directly based on the measurement of the WIM-system. As a part of the WIM-Hand project a multi-sensor WIM test site has been built at the A12/A50 highway near Arnhem in the East of The Netherlands. The test site consists of sixteen rows of sensors, each row consisting of four Kistler Lineas Piezo Quartz sensors. The length of each of the Kistler sensors is 1.0 meter, the spacing between each row of sensors is 1.5 meters. A full description of the design and installation of the test site can be found in (van Loo, 2001) and (van Loo, 2003). The system measures the wheel loads of all passing vehicles and stores the measured data from each sensor per vehicle in a database. Along with the measured data a number of video images of the vehicle are stored as well.

The measurement part of a WIM-system consists of the combination of the WIM-sensors and the surrounding pavement. As a result a WIM-system can only be calibrated when the sensors are installed in the road pavement. The basic idea of a multiple sensor WIM-systems is that by taking sufficient samples of the dynamic axle loads of the passing trucks the static axle loads can be calculated. The accuracy of most calculation algorithms is sensitive to the measurement error in the sampled axle load, except the neural network technique (González, 2003). That is why it is important that each sensor measures the exact value of the dynamic axle load the moment the axle passes over that sensor. This can be achieved if each individual sensor is dynamically calibrated. Dynamic calibration means that the sensor will be calibrated to the dynamic force measured by the measurement axle of the instrumented vehicle the moment it passes the sensor. As part of the WIM-Hand project an instrumented vehicle has been built to perform the dynamic calibration of the sensors of the WIM-Hand test site.

2. Design of the Vehicle

During the last decades several instrumented vehicles have been built and used for calibration and testing of WIM-systems. For example the vehicles from the Transport Road Research Laboratory in the UK (Cebon, 1999), the National Research Council of Canada (DIVINE, 1998) and the Technical Research Centre of Finland (Hutala, 1998). However these vehicles are either based on outdated computer technology or not available for long periods of time in The Netherlands.

The dynamic calibration of a WIM-system can be done in several ways: at a low speed with standard trucks or at a high speed with an instrumented vehicle. In the case of low speed calibration it is assumed that the dynamic part of the axle loads is negligible. Then the WIM-system can be calibrated to the axle loads that are measured when the vehicle is static. However, when the operational range of the WIM-system is tested at considerably higher speeds with such a standard truck, then the systems is in effect not calibrated for this operational range. Since the speeds at the test site vary around 80 km/h high speed calibration is preferred.

2.1 Vehicle Specifications

The key functional specifications for the instrumented vehicle for the WIM-Hand system include:

1. The vehicle has to measure and store the dynamic forces that are exercised by the measurement axle on the WIM-system;
2. The vehicle has to synchronise its measurements (in time) with the individual measurements of the WIM-system;
3. The sample frequency of the measurement systems should be more than 8 kHz to be able to synchronise with the WIM-Hand system;
4. The vehicle has to have a ‘quiet’ dynamic behaviour in order to minimise the dynamic component of load of the measurement axle;
5. The vehicle has to be able to measure at speeds from 10 to 100 km/h;
6. The vehicle has to be able to measure with axle loads from 5 to 15 tonnes;
7. The inaccuracy of the measurements of the vehicle should be 5% or less over the entire measurement range;
8. The calibration of the vehicle has to be traceable to international standards and approved by the National Metrological Institute. The calibration procedure will be an integral part of the certification for future WIM-systems for automatic enforcement.

3. Building of the Vehicle

3.1 Project Organisation

Kalibra International has been overall responsible for both parts of the project. The subcontractor for the development of the measurement system was TNO Automotive in Delft, the Netherlands. The subcontractor for the building of the custom-built trailer was Nooteboom Trailers BV in Wychen, the Netherlands. Furthermore, there were a number of other subcontractors for specific parts of the project, e.g. the axles and the tyres. The DWW only pays the costs that were directly related to the WIM-specific adaptation, while Kalibra only paid for the ‘standard’ truck and the trailer, custom-built for the static calibration of weigh bridges. The costs for the construction of the vehicle amounted to approximately Euro 600.000 to be paid by Kalibra. The costs for the WIM-specific parts, measurement systems and adjustments, approximately Euro 375.000 were paid by the DWW.

3.2 Measurement principle

The objective is to measure the force of one axle as directed between the tyre surface and the pavement (F_p). This is done by load sensors in combination with accelerometers. The load sensors (strain gauges) are mounted on the measurement axle between the spring centre and the wheel nave. These sensors measure the force of the trailer on the axle (F_a). This has to be compensated for the movement of the axles in order to get the axle load (F_p). This can be done by measuring the measured vertical acceleration (a) of the wheels and multiply it by the mass of the wheels (m_w). F_p is calculated using the following equation (1). A more detailed description of the measurement principle is given in (Hoogvelt, 2004).

$$F_p = F_a - m_w * a \qquad (1)$$

3.3 Specific Adaptations

The vehicle consists of a combination of a three-axle tractor with a five-axle trailer with a total length of 16.5 m. The maximum load is 44 tonnes, which results in a total maximum vehicle weight of 78 tonnes. Specific adaptations were made both to the tractor and the trailer.

The standard tractor has been replaced by a 6 x 4 DAF XF with 530 hp. The extra hp were necessary to be able to accelerate the total vehicle weight quickly enough to the required maximum speed of 100 km/h. Quickly means within 3.5 km, the distance between the WIM-Hand test site and the anticipated turning point. The measurement equipment and two of the liftable axles of the trailer can be controlled from the cabin. These two axles can be lifted when driving and can be controlled by a set of special buttons in the dashboard in the cabin of the tractor. The control of the measurement system is done in the cabin on a laptop PC with a wireless Ethernet connection to the measurement computer in the trailer. The measurement data can be saved on a CD or stored in the measurement computer. The cabin, a so-called space cab, has air conditioning and a safe for the storage of theft sensitive (computer) equipment.

Because of the required high total weight, a semi-trailer with five axles was selected. In order to avoid mechanical stresses in the measurement axle in short curves, the axles two to five are steerable. The first axle is the measurement axle and is not steerable, see Figure 1. Four of the five axles may be lifted (axles number 1, 2, 4, and 5). This way several axle loads can be realised on the measurement axle without changing the mass of the trailer. When the vehicle is not performing WIM-related measurements the measurement axle will be lifted to avoid unnecessary wear and tear of the sensors.

Figure 1 - Numbering of the Axles

Axles 2 and 4 can be lifted during driving, these axles will be lifted just before arriving at the WIM-system. This way the maximum load is not applied to the other axles any longer than necessary. This was necessary because the safety of the axles and the tires is guaranteed only for short distances at maximum speed and maximum axle loads. The tires are filled with nitrogen for heat conduction and to keep them up to pressure. The lifting of these two axles during driving is not possible in a standard hydraulic system, which is why an axle lift system has been designed that is capable of lifting the axles even with the highest axle loads. This system has a larger hydraulic pump than normal, with electronically controlled hydraulic valves.

3.4 Traceability

The traceability is one of the key issues for certification of WIM-systems. The calibration of the instrumented vehicle is an important link in the traceability chain of WIM-systems. The traceability chain consist of the following steps:

- a certified mass (certified by the Dutch Metric Institute (NMI));
- a certified load cell and accelerometer (certified by the NMI);
- the certified shaker used for the calibration of the vehicle (certified by the NMI);
- the instrumented vehicle (certification by the NMI in progress);
- the WIM-systems for automatic enforcement (certification by NMI in preparation).

The calibration of the sensors of the instrumented vehicle was performed by TNO, a detailed description of the calibration is given in (Hoogvelt, 2004). The use of a certified instrumented vehicle for calibration will be an important part of the criteria for certification of a WIM-system. In the Netherlands the NMI (Dutch Metric Institute) performs all test for certification of measurement instruments for enforcement agencies. Therefore, the NMI is the most logical institute to perform tests for certification of WIM-systems. How this will be organised in Europe is part of the REMOVE-project.

4. Use of the Vehicle

4.1 Measurement Principle

To be able to compare the measured signal from the WIM-system with the data measured by the vehicle, both systems must be synchronised. This is done using the exact time of the GPS-signal as a time reference for both systems. With the GPS-receiver the maximum difference in the time synchronisation is less than 10 μs. At the maximum speed of 100 km/h with a length of the tire/road contact surface of 30 cm, the contact time of the wheel on the sensor (width of 5 cm) is 12.6 ms. The sample frequency of the vehicle is 8 kHz and of the WIM-test system 8192 Hz (0.12 ms). This amounts to approximately 100 samples per axle load measurement.

4.2 Standard Operational Procedure

The load on the trailer is 44 tonnes, consisting of 44 mass pieces of 1000 kg each and a fork-lift truck for the on and off loading of the mass pieces. This way every axle load between 3 tonnes and 15 tonnes may be realised on the measurement axle. All mass pieces are certified and traceable to international standards. The lifting of the measurement axle is also used to compensate eventual off-set of the force sensors. This ‘zero-setting’ of the axle is done at the beginning of each measurement day. The lifting of one or more axles causes a change in the ‘driving height’ of the trailer. This change is detected and displayed, so the driver can adjust it electronically. The vehicle has a set of special permits to be allowed to drive with 70 tonnes at 100 km/h with axle loads of up to 15 tonnes. Nevertheless, the vehicle is detected as overweight by the WIM-NL systems, the systems used by the enforcement agencies, see Figure 2.

The type approval test of the WIM-Hand test site will consist of a large number of different runs by the instrumented vehicle. The runs differ in the following aspects:

- different axle loads on the measurement axle, i.e. 5, 10 and 15 tonnes;
- different speeds, i.e. 40, 60, 80, 100 km/h;

- different axles configurations, that is axles 2 and 4 lifted, or axles 4 and 5 lifted;

- different ways of driving over the WIM-system, that is accelerating, braking, and zigzagging;
- and during different weather conditions, e.g. different temperatures, rainy spells, over dry or wet surfaces, etc.

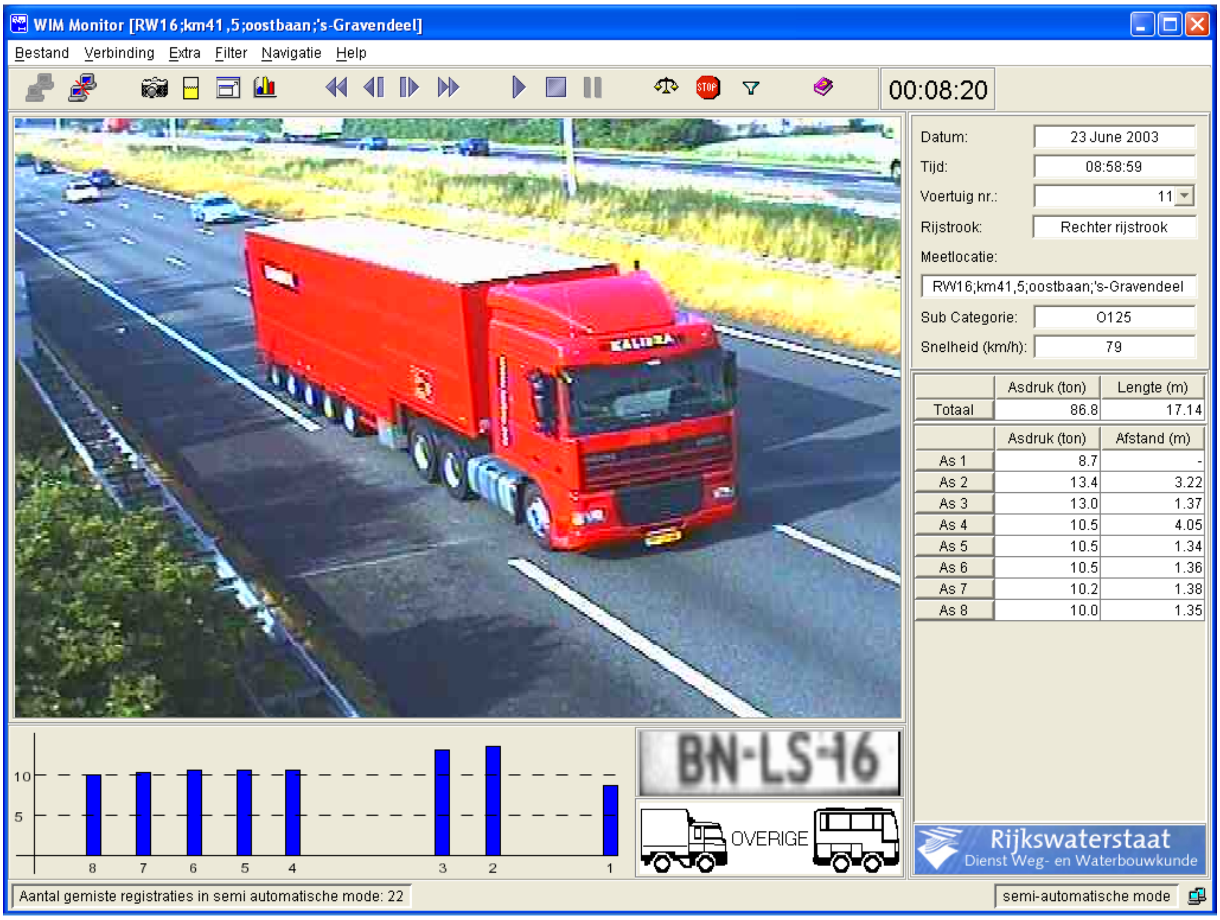

Figure 2 - The Instrumented Vehicle in Action

Which tests are deemed necessary for the type approval test is determined in cooperation with the NMI. The time interval between two calibrations will be determined based on the results of the type approval test.

4.3 Additional Applications

Although the instrumented vehicle was built for the purpose of calibrating the WIM-Hand test-system, the vehicle can be used for a number of other applications as well. Possible other applications are:

- Calibration of static weigh bridges or weighing scales;
- Calibration of other WIM-systems. For this calibration it is necessary that the measurements of the vehicle can be synchronised in time with those of the WIM-system;

- Effects of road surface irregularities on the dynamic loads. Possible areas of interest are the dynamic loading of bridges, spatial repeatability, or other issues in vehicle road interaction.

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AUTOMATIC OVERLOADING CONTROL TEST SITE IN FRANCE

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Abstract

The French Public Works Research Laboratory is delegated by the Ground Transportation Division of the French Department of Equipment and Transportation a mission dedicated to improve the trucks overloading control effectiveness. This is achieved by proposing a reliable and accurate Weigh-In-Motion (WIM) system including automatic vehicle identification and enforcement. An experimental site will be implemented in 2005 on national road 4 (RN4), associating Multiple Sensor WIM, overloaded vehicles preselection with image capture, and Low-Speed WIM. This paper will present the test site description, and the method used to reach the objectives.

Keywords: Weigh-in-Motion (WIM), Preselection, MS-WIM, Video, Specification, Accuracy, Trucks.

Résumé

La Direction des Transports Terrestres (DTT) délègue au Laboratoire Central des Ponts et Chaussées une mission dont l'objectif est d'améliorer l'efficacité des contrôles des poids lourds en mettant à la disposition de la DTT un système de pesage en marche fiable et précis permettant une identification et une verbalisation directe des poids lourds en surcharge. Pour répondre à cette demande, un site expérimental pilote sera installé en 2005 sur la Route Nationale 4, associant le pesage multicapteur, la présélection des surcharges avec prise d'image ainsi que la pesée à basse vitesse. Cet article présente le site et la méthode qui sera employée pour atteindre l'objectif fixé.

Mots-clés: Pesage en Marche, Présélection, MS-WIM, Vidéo, Spécification, Précision, Poids Lourds.

法國自動化超載控制試驗場

摘要：

法國公共事務研究實驗室接受法國基礎設施與運輸部之陸地運輸局的委託，進行增進卡車超載控制效率之研究。爲了達成此一目標，該單位採用一套可靠度高且精確的動態地磅 (Weigh-in-Motion, WIM) 系統，其包含自動車輛辨識與執法系統。實驗場將於 2005 年在四號國家道路啓用，儀器設備包含多重式感測器動態地磅系統、影像處理預選超載車輛，以及慢速動態地磅。本篇文章將針對試驗場之配置以及達成上述目標之方法進行說明。

關鍵字：動態地磅、預選、複合感測器之動態地磅系統、影像、規格、正確性、卡車

1. Introduction

The French Public Works Research Laboratory (LCPC) associated with the Eastern France Technical Centre (CETE de l'Est) was asked by the Ground Transportation Division of the Ministry of Transport to carry out a wide project of overloading controls efficiency improvement on national road network. Different tools will be used to reach this purpose.

First, Low-Speed WIM (LS-WIM) systems should allow short term effective enforcement, as the first French type approval for LS-WIM systems might be delivered soon. Accuracy reached by these systems, class A(3) to A(5) according to the COST323 Specifications (COST323, 1999) complies with enforcement requirements.

Preselection systems, coupling a High-Speed WIM system (HS-WIM) composed of two piezoceramic strip sensors and a video camera, are under experimentation since 2001 (Stanczyk & Marchadour, 2005) in eastern France, and led to significant improvement of overloading controls efficiency. Only vehicles which were measured as overloaded by the HS-WIM system and identified with the video and statically weighed and enforced.

Multiple-Sensor WIM (MS-WIM) systems (composed of app. 5 to 20 piezoceramic strip sensors) were improved during WAVE European project 1996-99 (WAVE, 2001). However, ongoing research might allow to reach enforcement accuracy requirements while weighing at normal speed and within the traffic lane.

Thus, it was decided to implement a test site associating those three systems, with two goals : performing efficient overloading controls while developing future automatic systems for enforcement. Researches with this fully automatic weighing prototype will lead to determine the optimised design of effective and reliable systems (number of sensors, video quality, etc…), and to validate the results obtained from simulations (Labry et al., 2004, Labry et al., 2005a). A test site meeting the quality requirements of COST323 specifications was identified on national road 4 (RN4) in Eastern France. This paper proposes to describe the whole process of automatic weighing as it was planned, and a description of the test site.

2. Test site location

The test site is located on RN4 between Nancy and Paris, on the slow lane of East-West direction, in Maulan (Figure 1). It was chosen as convenient for an overloading preselection system coupled with a MS-WIM array, according to 5 main criteria:

- Geographical situation : a 30,000 m² area was available after the planned WIM station location. A trucks parking lot will be built by the end of 2004. The parking lot will be equipped with a LS-WIM system in early 2005.
- Pavement structure : the pavement is semi-rigid, which is appropriated for piezoceramic strip sensors. A new bituminous layer was made in November 2003. This should allow to avoid any need for a new layer covering the installed sensors within the next years.
- Communication network and energy supplying : on this route, there are many possible locations to install the WIM sensors, but only Maulan site provided telephone and electricity networks less than 200m away.

- Protection against vandalism and operators safety : the site is close to the Maulan village, and there is a safety barrier along the road.
- Truck traffic: 4823 trucks / day recorded in 2003.

The sensors are located on a semi-rigid structure pavement, with a longitudinal slope under 1% (Figure 2). The road profile was characterised with the Longitudinal Profile Analyser (APL) and obtained the following ratings : 8.6 - 9 - 8 respectively for short, medium, and long wavelength, the International Roughness Index (IRI) being : 1.17m/km. This site was found to be a good WIM site (class II) according to COST323 European specification (COST323, 1999).

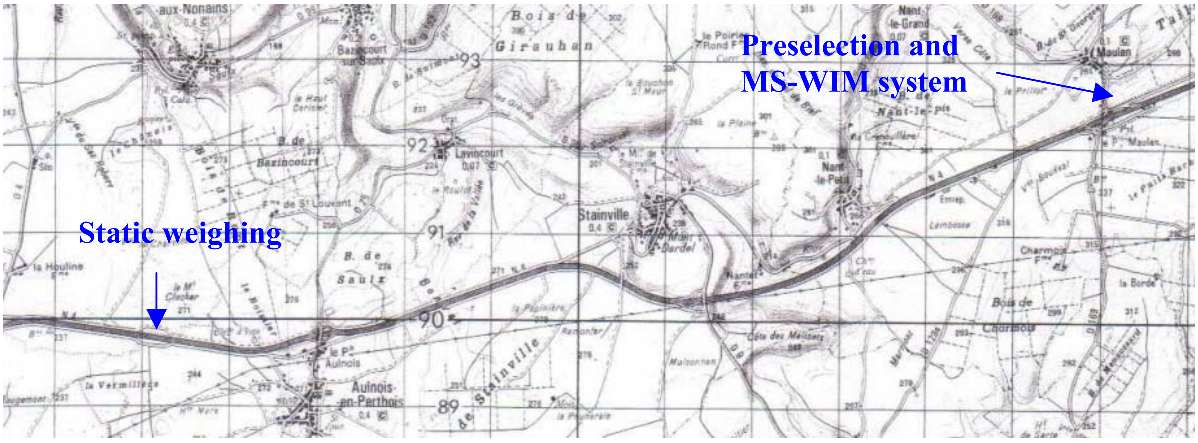

Figure 1 - Preselection, MS-WIM and LS-WIM Test Site Locations

Figure 2 - Preselection and MS-WIM Site

3. Weighing Systems

The experimental site will be equipped with three devices (Figure 3):

- A MS-WIM system, to implement the algorithms developed in WAVE, to check the real accuracy and to allow the future development of a reliable and accurate automatic weighing system for enforcement. This system will be installed 13km before the Maulan rest area.

- Among the MS-WIM array sensors, two piezoceramic bars will be used to screen the overloaded vehicles, coupled with a video system. As soon as a truck will be measured as overloaded by the WIM system, a picture will be sent through the telephone network to a PC on the parking lot.
- A LS-WIM system on the rest area, approved for enforcement both in static and at low speed.

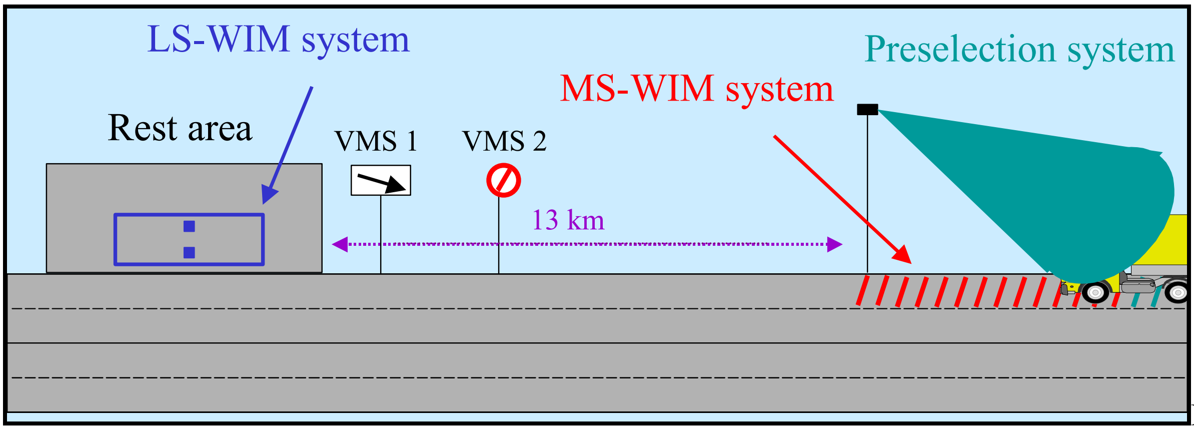

Figure 3 - Layout of the Whole Enforcement Process

3.1 MS-WIM System

The MS-WIM system will consist in (Figure 4):

- A 16 piezoceramic sensors array, designed according to the methods presented in (Labry et al., 2005b),
- Two wheel transverse location detection systems : one before the first sensor of the array, and the other one after the last sensor, in order to correct any “ sensor edge effect” (Labry et al., 2005a),
- A temperature sensor.

Those sensors will be connected to the WIM electronics, and to a PC on the rest area, where those data (transverse location, calibration factor, pavement temperature, and WIM) will be visualised and stored, for each vehicle.

Labry et al (2005a) showed the piezoceramic sensors sensitivity to wheels transverse location. Some correction laws were proposed. Results will have to be validated with these real data.

The temperature data will be used to evaluate how much the weighing and the automatic calibration is influenced by the temperature variations. Moreover, a further investigation will be carried out to compare the efficiency of the automatic calibration and a calibration based on the use of the vehicles weighed on the rest area (statically or at low-speed).

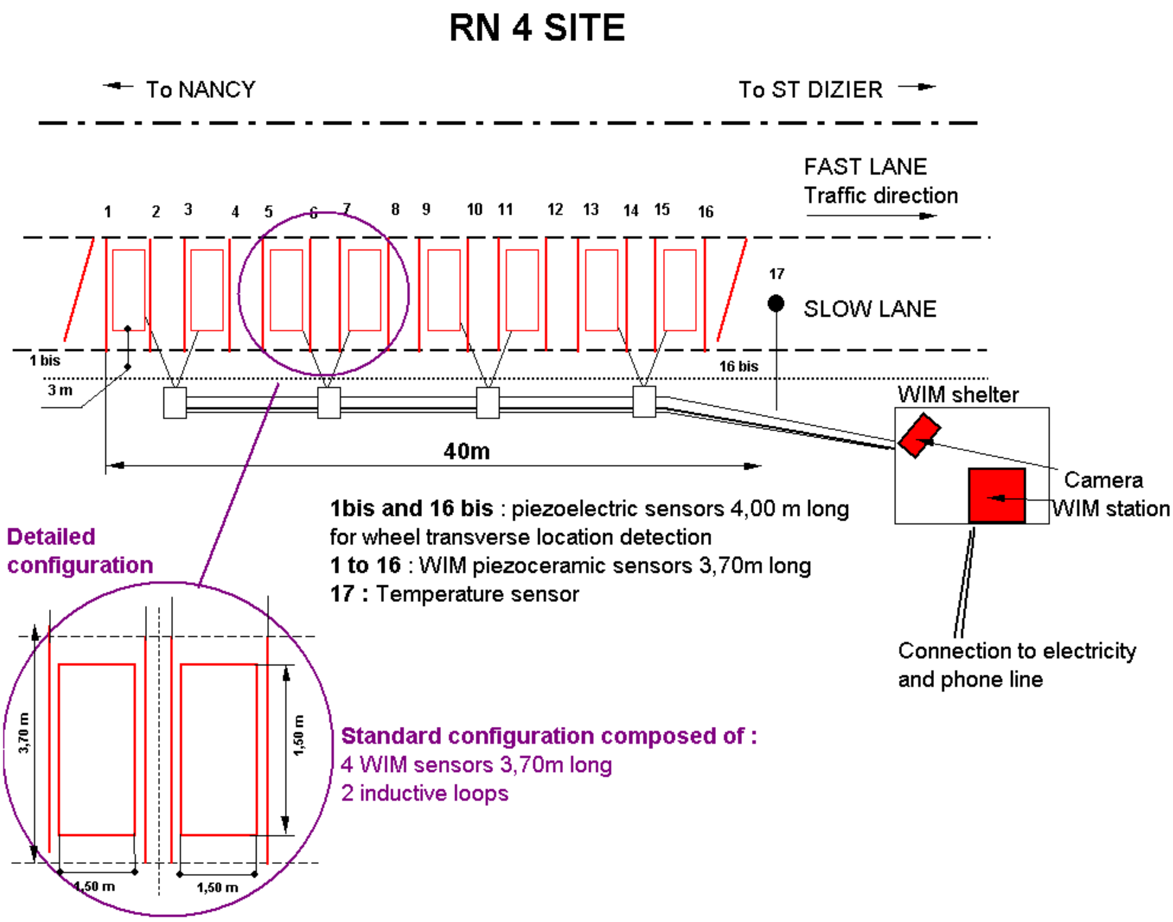

Figure 4 - MS-WIM Array Presentation

Measured WIM data will then be computed with algorithms (WAVE, 2001) to estimate trucks axles and gross static weight. Then, algorithms performances will be compared.

The Signal Reconstruction and Kalman Filtering Method was developed in LCPC (Sainte-Marie et al, 1998). This deterministic approach consists of a reconstruction of the continuous dynamic axle impact force signal, using the sample of impact forces measured by each sensor of the MS-WIM array. Then, the static axle load is estimated by the mean of the reconstructed signal, on a given road length (L). L depends on bouncing and rolling frequencies, which are estimated by an extended Kalman filtering procedure.

This method was developed by CUED (Stergioulas et al., 1998) and is a probabilistic method based on a Maximum of Likelihood estimator and a signal modelling of the dynamic forces. The theoretical analysis considers two generic vehicle models and simple approximations: (LK1) a quarter car model, whose tyre force spectrum can be reasonably approximated by a single sine wave (low frequency mode (1.8-4 Hz) corresponding to the body vehicle bounce), and (LK2) a 'walking beam' model, whose tyre force spectrum can be approximated by two sine wave components (one for low frequency mode and the other for high frequency mode (10-15 Hz) corresponding to the axle hop). Then, assuming that a random noise is added to the tyre force signal, the Maximum of Likelihood method gives an estimation of the model parameters: static weight, the signal amplitude(s), phase(s) and frequency(ies).

Those methods will be compared to the simple average estimation. Indeed, assuming that the spatial mean of the axle impact forces is equal to the static axle load leads to average these dynamic loads, measured by a set of uniformly spaced sensors. Further comparison with other algorithms developed abroad might be carried out.

3.2 Preselection System

The preselection system will be designed according to the two experimental preselection systems installed on national road RN83 and on motorway A31 (Stanczyk et al., 2005). The preselection system will handle:

- Axle load and speed measurements,
- Overloaded trucks detection and identification, with a video and an Optical Character Recognition software (OCR) for automatic reading of trucks registration plates
- Real time transmission (by telephone network) of overloaded trucks pictures to the static and low-speed weighing area. Loads, speed, truck's manufacturer name, and estimated time of arrival on the rest area, will be sent within the picture (Figure 5).

Figure 5 - Picture and Data Transmitted

These data will also be used for statistical purposes or automatic control. Controls in transport companies will be focused on the companies that have often been identified as overloaded.

As the Ground Transportation Division will install 10 of those preselection systems on the French road network in 2005, and 30 more later, it was also planned to record the trucks registration plate and their speed, on each preselection site, and eventually on other dedicated sites, to enforce the trucks mean speed between two sites.

3.3 LS-WIM system

The rest area will be built by the end of 2004, along the RN4, near "Rupt-aux-Nonains". The first phase includes the realisation of a 15 trucks parking lot and a 23 cars parking lot (Figure 6).

During the beginning of 2005, a 36m long concrete slab will be installed, in order to receive an axle load scale. The weighing scale will allow both static and low speed weighing with the same electronic device. The system will have to be approved by legal metrology for both applications. The LS-WIM should allow to dramatically decrease the weighing time, compared to the static weighing. Indeed, 7 min are approximately necessary for a 5-axles truck static weighing, and LS-WIM system is expected to divide this time by 7 to 10. The whole system will consist in:

- Two variable message signs (VMS), which will be installed between the WIM sites and the rest area : the first one, 800m before the parking entrance, will, when activated, inform the trucks drivers that overtaking is forbidden in this zone; the second one, 200m before the parking entrance, will lead the overloaded vehicle to enter the weighing site,
- A weighing scale, embedded in the middle of the concrete slab, with data acquisition software,
- A bicolour light sign, which will control the trucks traffic on the rest area before the weighing system. The light could be controlled by an operator, or by a pair of inductive loops for an automatic operation (before and after the weighing scale).
- A sign installed after the weighing scale will control the trucks direction. Overloaded trucks will be led to static weighing as long as the LS-WIM system is not approved for enforcement. Other trucks will be led back to the national road. This sign should be connected to the station in order to be automatically controlled.
- A second phase will lead to implement a camera with a OCR software just after the slab, in order to automatically read the registration plate. A picture of each overloaded vehicle will be taken and saved with loads and registration plate data. This further development, coupled with automatic trucks traffic regulation on the test site, would allow decreasing trucks latency and fining delay, and would contribute to improve the weighing efficiency.

The whole weighing process tends to be as automatic as possible.

While performing controls, the first VMS will be activated. When the preselection system identifies an overloaded vehicle, the weighing operator receives the associated picture and data, including the estimated time of the truck arrival. Just before this time, the operator activates the 2nd VMS. A policeman will verify that the procedure is respected. If a driver does not respect the VMS indications, a motorcycled policeman will ensure the vehicle interception. The LS-WIM is then performed, monitored by the bicolour light and the exit sign.

Some efficiency improvement could be expected as soon as the vehicles would be equipped with tags storing legal information (load limits). Indeed, this legal information is, at this time, only available on legal document and has to be asked to the driver before the weighing.

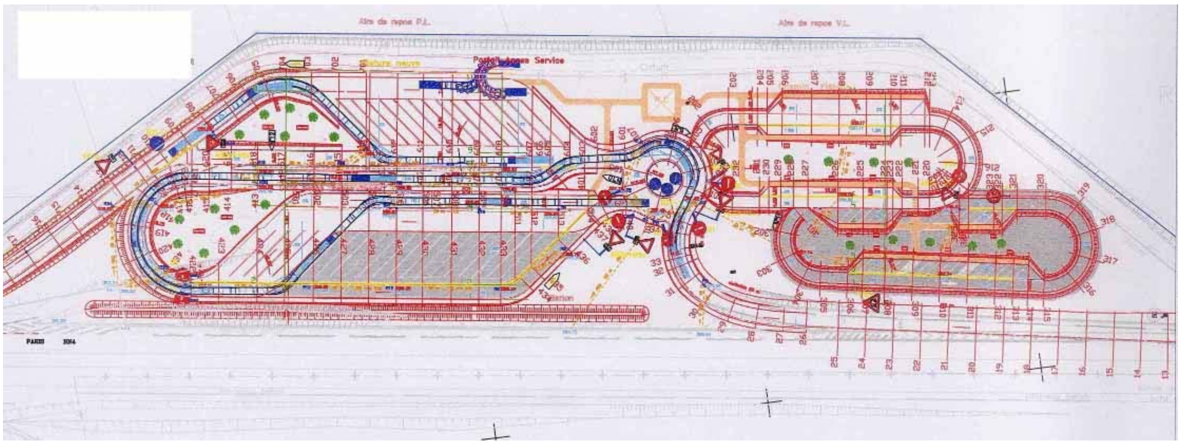

Figure 6 - Parking Lot

4. Test Plan

The whole sample composed of trucks from the traffic and statically weighed will be divided into sub-samples to carry out analysis under different repeatability and environment reproducibility conditions (according to COST323 European specification). Four test trucks will be used :

- A light 2-axles rigid truck (3.5 tons),
- A rigid 2-axles truck (19 tons),
- A 3-axle truck with a tandem, with a 2 or 3-axles trailer (40 tons),
- A 2-axle tractor articulated with a trailer with a tridem (30 tons).

Season and temperature influence will be analysed. Validity of the automatic calibration factor will be checked. Correction laws with respect to wheel transverse location will be calculated and evaluated. MS-WIM algorithms will be compared. Conclusions will be given about MS-WIM and preselection accuracy, and enforcement applications feasibility.

5. Conclusion

This test site will lead to important conclusions for overloaded trucks future enforcement at normal speed (preselection and MS-WIM systems).

Loads control methods might be significantly modified compared to the static legal weighing. This will induce some communication effort with local administration and weighing operators.

This test site is expected to improve overloading and overspeeding controls efficiency, once the LS-WIM system will be approved by French legal metrology.

According to the results (optimised array design, number of sensor, static weight estimation algorithms performances), the future automatic enforcement systems at normal speed will be designed.

Before any enforcement application with WIM systems, a type approval is needed. It took a significant time to prepare the approval process for LS-WIM systems, and it might take longer for WIM systems at normal speed. National and international metrology organisations might collaborate with WIM experts in order to prepare the future type approval, and the evaluation procedures.

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COMMERCIAL VEHICLE LOADING IN AN URBAN ENVIRONMENT



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Abstract
Increasing commercial vehicle operations on highways is resulting in increased structural depreciation of our road infrastructure assets. This increase in commercial trucking is also increasing truck loading on urban pavements. By actively monitoring and quantifying commercial truck loadings and reducing the amount of overloading, it may be possible to better design and extend the life of road and bridge structures. This paper presents the pilot implementation of a weigh in motion (WIM) and video surveillance system installed in Saskatoon, SK. Specifically this paper will present commercial vehicle loading data collected in an urban environment, quantify overloading that is occurring, and what the effects of this overloading is having on the roadway infrastructure.

Keywords: Weigh in Motion (WIM), Surveillance, Urban, Overloading.

Résumé
L'augmentation du trafic des véhicules utilitaires sur les routes accroît la dégradation des structures et infrastructure routières. Cet augmentation du transport par camion conduit aussi à un accroissement des charges de véhicules sur les chaussées urbaines. Par un contrôle actif quantifiant les charges des camions et réduisant le taux de surcharge, il est possible d'améliorer la conception et de prolonger la durée de vie des routes et des ponts. Cet article présente la mise en œuvre expérimentale d'un système de pesage en marche (WIM) et de surveillance vidéo installé à Saskatoon, SK. On présente en particulier les données de charge de véhicules utilitaires recueillies dans un environnement urbain, les occurrences de surcharges et les effets de ces surcharges sur l'infrastructure des chaussées.

Mots-clés: Pesage en Marche, Surveillance, Urbaine, Surcharge.

歐洲動態地磅之發展現況

摘要：
此篇論文提供了歐洲在動態地磅 (Weigh-in-Motion, WIM) 最新發展的回顧。全歐洲及各國有關動態地磅之國家計畫均囊括在內，另亦包括感測器技術之發展和系統設計。而最受矚目的是目前正在發展的多重感測器動態地磅系統。文中亦探討全自動載重系統的雛型，其中科技之研發與法律相關架構則是絕對必要之重點。自第三屆國際動態地磅研討會以來，橋樑式動態地磅的商業化已在發展中，而此一系統正持續朝向零養護之方向發展。文中同時亦探討動態地磅於鋪面與橋樑設計與評估之應用。

關鍵字：動態地磅

1. Introduction

This paper examines the traffic loading data obtained from a WIM site on an urban freeway in Saskatoon, Canada. WIM systems are typically used in one of two applications, data collection and vehicle pre-screening at weight enforcement facilities. The WIM system collects individual axle weights, spacing between axles, and speed for each vehicle and uses this information to determine axle group weights, gross vehicle weight and vehicle classification. Depending on the application, each vehicle record may be examined in detail, or data may be considered as it represents the total traffic flow. In this study, the WIM system was used to determine the magnitude and characteristics of overloading including the number, severity, and timing of overloading and the types of vehicles responsible. The application of the WIM system installed in an urban setting for planning, design and preservation as well providing a tool for increasing enforcement efficiency is discussed.

2. Site Description

The WIM system used in this study is located in the two northbound lanes of Circle Drive, an urban freeway, in the south-eastern part of Saskatoon. Circle Drive is a grade-separated freeway with a posted speed limit of 90 km/hr. Circle Drive is one of two truck routes for truck traffic through the city as well as a key arterial for intracity traffic. The alternate truck route through Saskatoon for trucks coming from the southeast leads through the downtown area and therefore is not a desirable route for much of the through traffic.

Two of the main highways that serve the south side of Saskatoon are Highway 16, also known as the Yellowhead, which is a main east-west trade corridor through western Canada, and Highway 11 which is a connecting highway from the city of Regina.

3. Video WIM Technology

The equipment installed at this site includes two WIM technologies, a load cell scale in the right lane, where the majority of the truck traffic is expected to travel, and a quartz axle sensor array in the left lane. A video image capture system is also installed at the site. The load cell scale meets the Type III accuracy requirements (+/- 6 percent on GVW, 95 percent confidence) as defined for WIM applications by the American Society for Testing and Materials (ASTM) E1318-00). The quartz axle sensor array provides WIM data with accuracy as specified by ASTM E1318-00 Type I (+/- 10 percent on GVW, 95 percent confidence) (ASTM, 2000). The data recorded from the WIM equipment includes individual axle, axle group, and gross vehicle weights, axle spacing, and vehicle speed. The video camera and video image capture card capture an image of every commercial vehicle crossing the WIM installation. The image is correlated to the vehicle weight record and stored together. The data file can be retrieved at any time and the records viewed to see what types of trucks are using the freeway and whether they are complying with specified weights and dimensions regulations.

The video information can also be viewed in real-time using a web-based application. A web-site address has been provided that links a user with appropriate access provisions directly to the road-side computer. When connected to the web-site, the user can view the image and vehicle record, including axle weight and separation, of each truck as they pass the site and select particular trucks based on time or sequence number for detailed examination. Access can be gained from a variety of internet capable devices including some hand-held personal digital assistants.

4. Commercial Traffic Loading Patterns and Profiles

Prior to the installation of the WIM system there was no comprehensive and continuous data available that could be used to quantify continuous traffic conditions and to quantify overloading if present. With the installation of the WIM, the analysis evaluates overweight vehicles, which in this context is defined as any vehicle that exceeds the normal allowable weight for that category of vehicle. In the analysis no distinction is made between trucks that may be legally overweight due to permits or exemptions, and those that are illegally overweight. The discussion includes overweight vehicles in two categories, those that exceed the allowable GVW are labelled as “GVW Limits”, while those that exceed one or more of the applicable axle, axle group, or GVW limits are labelled as “Axle or GVW Limits”.

5. Data Collection and Traffic Characterization

Data was collected from the site during a one week period from September 4th to 10th, 2002, a time period that did not include a long weekend or any holidays. For the chosen time period primary allowable weight limits were in effect.

Weights and dimensions regulations in effect on this roadway segment were applied to determine the characteristics of commercial vehicle weights. The classification scheme used by Saskatchewan Highways and Transportation was used to determine maximum allowable weight limits by vehicle type. Approximately 5000 vehicle records were compiled and analyzed, with each vehicle record including individual axle weights, spacing between axles, and vehicle speed. The range of vehicles covered was from two axle single units, Federal Highway Authority (FHWA) Class 5, up to eight axle multiple trailer units, FHWA Class 13. Configurations of nine axles or more are only allowed by permit and account for approximately one percent of the commercial vehicle stream. These vehicles were excluded from the analysis since the allowable weight varies depending on the permit issued, so determination of excess loading is not possible without knowing the specific permit for each vehicle.

For analysis purposes, the truck population observed on Circle Drive was divided into five representative categories as follows:

- FHWA Class 9: Five axle semi-trailer
- FHWA Class 10: Six axle semi-trailer
- FHWA Class 13A: Seven axle combination unit
- FHWA Class 13B: Eight axle combination unit
- Other: All other trucks, 85 percent of which are two and three axle single units

The percentage of each truck type is illustrated in Figure 1 and summarized in Table 1 along with other vehicle class specific information. Over 40 percent of the trucks observed on Circle Drive were Class 9, with approximately 20 percent of trucks in each of the Classes 10, 13B, and other categories. The remaining two percent of the trucks observed on Circle Drive were Class 13A.

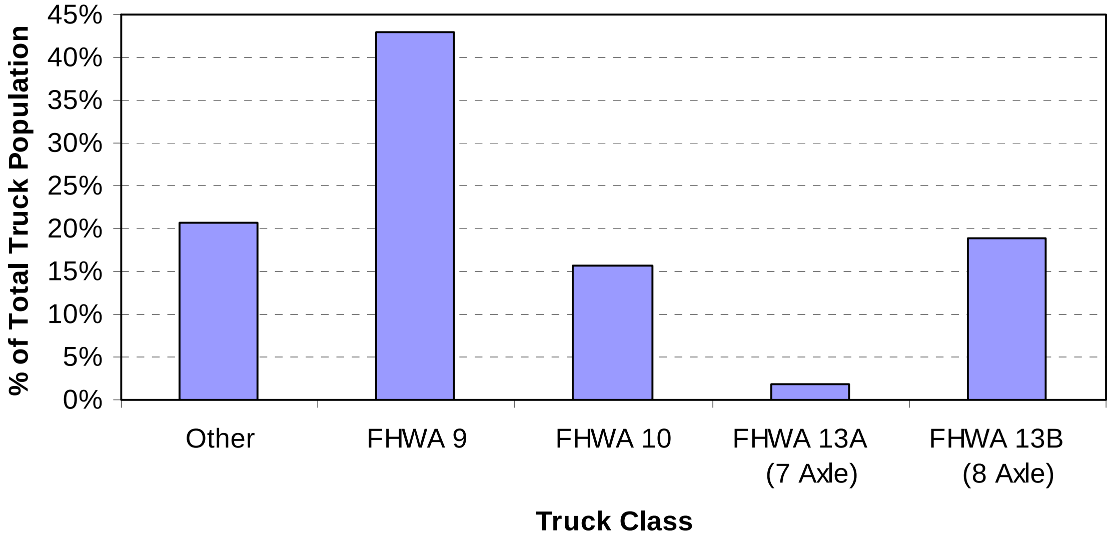

Figure 1 - Truck Class Distribution: Percentage of Each Class

Table 1 - ESALs due to overloading by various truck types

	VEHICLE CLASS					
	Other	FHWA 9	FHWA 10	FHWA 13A	FHWA 13B	Total
1. # of Trucks	1021	2114	779	94	925	4933
2. % OF Total Trucks	20.7%	42.9%	15.8%	1.9%	18.8%	100%
3. # Overweight (Axle and/or GVW Limits)	104	141	103	17	265	630
4. % Overweight (Axle and/or GVW Limits)	10.2%	6.7%	13.2%	18.1%	28.6%	12.8%
5. # Overweight (GVW Limit)	25	26	14	6	39	110
6. % Overweight (GVW Limit)	2.4%	1.2%	1.8%	6.4%	4.2%	2.2%
7. Total ESALs for class	619.1	2105.8	895.4	183.9	2465.9	6270.2
8. ESALs due to overloading	127.5	72.0	55.9	14.7	120.8	390.9
9. % ESALs due to overloading within class	20.6%	3.4%	6.2%	8.0%	4.9%	6.2%
10. % of total ESALs from class	10%	34%	14%	3%	39%	100%
11. % of total ESALs due to overloading from class	33%	18%	14%	4%	31%	100%

6. Temporal Distribution of Commercial Traffic

One area of examination that will help to define commercial vehicle traffic patterns is the temporal occurrence of truck traffic, and the potential temporal occurrence of overloading. There are often underlying trends and patterns in traffic such that conditions change on a somewhat routine and predictable basis. These trends may be revealed by characterizing the temporal distribution of the commercial traffic. An obvious example is peaks in traffic demand during the morning and evening rush hours on an urban freeway. Although they may not be as obvious, there may be daily, weekly, and seasonal trends in commercial vehicle activity as well.

The truck traffic volume throughout the study week is illustrated in Figure 2. The lowest truck volumes (345) were observed to occur on Saturday. The weekday volume was fairly uniform and significantly higher than the weekend volume. The highest traffic volume occurred on Monday (905), followed by Thursday (853) and Tuesday (819). Average weekend volume was 424.5 trucks per day, while the average weekday volume was 816.8 trucks per day, almost twice the weekend average.

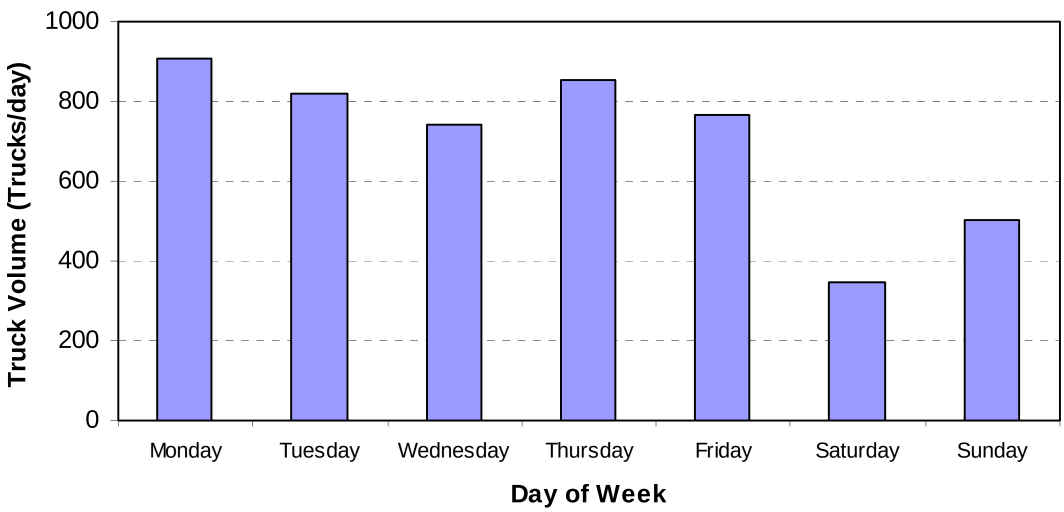

Figure 2 - Truck Volumes by Day of Week

The hourly traffic volume is illustrated in Figure 3. There is a general trend of low volumes in the morning and evening, with higher traffic volumes through the middle of the day, with truck volumes near 300 per hour through most of the mid-day period.

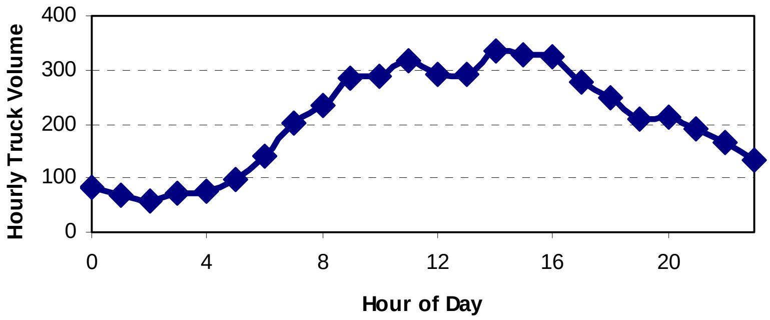

Figure 3 - Truck Volume by Time of Day

The rate of overweight occurrences throughout the week are illustrated in Figure 4. Recorded overweights indicate a decreasing trend from the beginning of the week to the end of the week. The highest percentage of overloading occurred on Monday at 18.6 percent and declined each day, with the exception of Friday, with a low of 5.5 percent on Saturday. Although no correlation has been identified, it is interesting to note that Monday was also the day that had the highest truck traffic volume. While there is not as clear a trend throughout the week when the GVW limits are considered, Monday still clearly has the highest rate of vehicles exceeding allowable weight limits at 3.4 percent, more than one percent greater than any other day of the week. The lowest rate of exceeding GVW limits occurs on Sunday at 1.4 percent. Overloading rates of approximately two percent were observed for all other days, varying by no more than +/- 0.3 percent.

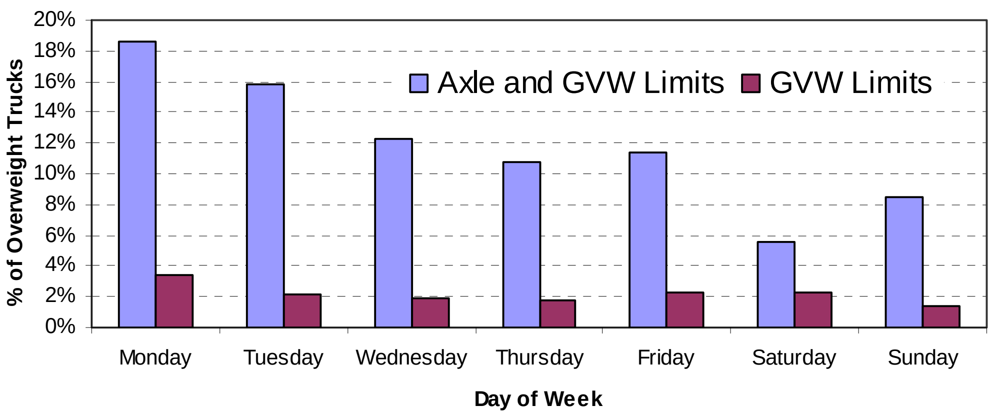

Figure 4 - Percentage of Vehicles Exceeding GVW and All Limits By Day of Week

The rates of overweight occurrence by time of day are illustrated in Figure 5, broken down into three hour time periods.

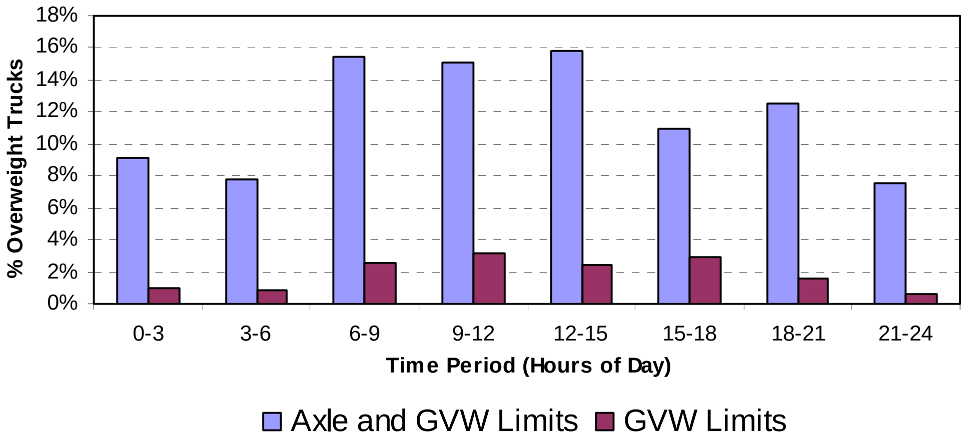

Figure 5 - Percentage of Vehicles Exceeding GVW and All Limits by Time of Day

The late morning and early afternoon period, starting from 6 am and ending at 3 pm, had the highest rate of trucks exceeding one or more limits, with more than 15 percent of trucks overloaded during this time period. During the period of 6 am to 9 pm, rates were all in excess of 11 percent, while the highest rate outside this period was 9.1 percent. Similar results can be seen when the rate of GVW overweight occurrences are examined. Between 6 am and 6 pm, greater than 2.6 percent of all trucks exceeded the allowable GVW. Between 6 pm and 6 am 1.6 percent or less of all trucks exceeded the allowable GVW.

Comparing the daily traffic volumes presented in Figure 3, shown above, and the overloading rate in Figure 5, it is noted that the highest rates of trucks exceeding allowable limits (axle and GVW and GVW only) correspond to the time periods of highest truck volume. One possible explanation for this phenomenon may be the increase in localized traffic that occurs during business hours. The closest permanent weigh stations are 25 or more kilometres from Saskatoon and therefore have little enforcement effect on the local traffic. During evening and early morning hours, the truck traffic would be expected to have less local trucks and more long haul trucks, which have been exposed to more permanent enforcement facilities and therefore have greater compliance with regulations.

7. Role of WIM in Urban Weight Enforcement

A WIM system can play an important role in improving the effectiveness of weight enforcement in an urban environment. Since resources are typically limited for weight enforcement in an urban setting, it is important to use those resources in the most effective way possible. A WIM system can be part of planning and evaluating enforcement strategies and can also be an active part of the enforcement effort with the addition of video capabilities.

7.1 Planning and Evaluation of Enforcement Efforts

One approach to improve the effectiveness of enforcement efforts is to strategically select the time and place of enforcement efforts. From the daily and weekly overloading patterns presented earlier, a strategy could be developed as to when enforcement should be done to have the greatest effect. As illustrated in Figures 4 and 5, the times of most frequent overloading were early in the week, particularly Monday, and during the working day.

The WIM data could also be used to target particular classes of vehicles for specific attention. Overall, it was found that 2.2over 2 percent of commercial vehicles exceeded the allowable GVW and 12.8 percent of the commercial vehicles exceeded one or more of the axle, axle group, or GVW weight limits. Figure 6 provides a breakdown of the overweight occurrences in terms of GVW only and axle and/or GVW, for the various classes of vehicles. Class 9 vehicles had the lowest frequency of overweight occurrence, 1.2 percent on GVW limits and 6.7 percent on axle and/or GVW limits. The FHWA 13A and 13B classes had the highest rate of exceeding weight limits, with rates of 6.4 percent and 4.2 percent respectively in excess of GVW limits, and 18.1 percent and 28.6 percent respectively in excess of axle and/or GVW limits. Class 10 and the other grouping with two and three axle trucks had excess GVW weights in 1.8 percent and 2.4 percent of trucks respectively, and excess on axle and/or GVW limits in 13.2 percent and 10.2 percent of trucks respectively.

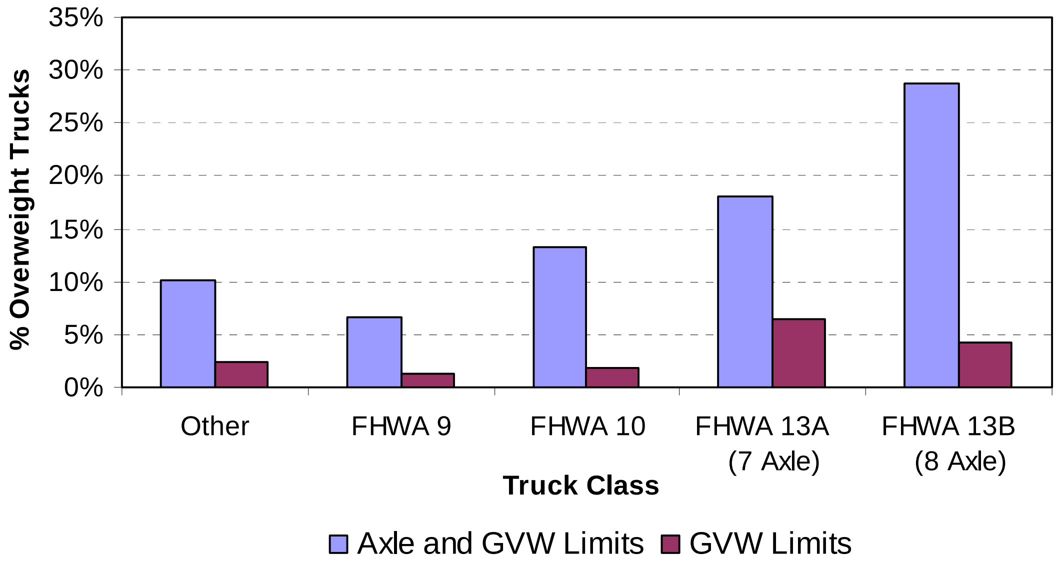

Figure 6 - Trucks Exceeding GVW and Axle Weight Limits: Percentage by Class

The WIM system can provide data for measuring the effectiveness of any enforcement efforts that are employed to determine what the reduction in overloading violations was and how long the reductions lasted. This information feeds back into the strategy development to determine what frequency, timing, and level of enforcement is needed. Enforcement efforts are often measured in terms of number of vehicles weighed and number of citations given, but these measures show the effort expended, but do not provide a measure of the desired outcome. More appropriate evaluation methods that consider proportion of overweight trucks, severity of overweight trucks, and excess ESALs have been proposed, all of which are available from the WIM system (Hanscom and Goelzer, 1998).

7.2 Video WIM as an Enforcement Tool

The Video WIM system that is operating on Circle Drive can be used as a tool to improve the effectiveness of weight enforcement efforts. Temporary enforcement set-ups that are commonly used when fixed facilities are not available are limited in the number of vehicles that can be processed, with a thorough inspection taking approximately 45 minutes to conduct. For the vehicle driver and enforcement personnel, the most effective approach is to examine the trucks with the highest likelihood of being in violation (Shamo, 2002). Real-time access to video and weight information allows enforcement personnel to increase their effectiveness by selecting only vehicles with a high potential of being in violation. Video images can also be reviewed at a later time, possibly on a weekly or monthly basis, and a trend of repeat offenders may be identified. The result of identifying such a trend could be an "encouragement" letter asking for cooperation from the carrier to rectify the problem, or the pursuit of legal action against the repeat violator for causing damage to the highway infrastructure.

A future step in the use of video enforcement could be an unmanned automated roadside enforcement system that would produce citations based on WIM and vehicle identification technology on a 24/7 basis, similar to photo-radar or red-light cameras. Under current operational and judicial restrictions, this type of system is not currently possible, and advances in technology and changes in laws will be necessary for implementation (Andrle et al., 2002). However, the video WIM system is a step in this direction and may lead to further developments and changes in enforcement practices.

8. Conclusions

A WIM and video capture system installed in an urban freeway setting was used to determine the extent and patterns of overloading by commercial vehicles. It was found that almost 13 percent of commercial vehicles were in potential violation of the applicable axle, axle group and gross vehicle weight limits, of which more than two percent were in excess of the allowable GVW. Patterns were identified showing the truck types most likely to exceed limits as well as the time of day and days of the week when overloading was most likely to occur.

The analysis showed that the greatest contributor of loading in excess of legal limits were the two and three axle vehicles, which are typically local service vehicles. The analysis also showed that the largest amount of overloading occurred during the workday hours, which is the time when local trucks would be expected to be the most active. Enforcement efforts are often targeted at the larger vehicle types, but the results of this analysis suggest more attention should be paid to two and three axle trucks. The overloading that is taking place has a negative effect due to the increased structural depreciation of the city's road asset.

The WIM and video capture system used to gather the data needed to understand the problem of overloading can also act as part of the solution. Several applications of this equipment to more effective enforcement activities were identified including developing a strategy of when, where and who to enforce, screening and identification of most likely violators in real time, identification of repeat offenders, and evaluation of the effectiveness of enforcement efforts.

Further research is recommended in the following areas to provide better understanding of commercial vehicle loading in an urban environment:

- The relationship between excess loading on urban freeways and the economic damage caused at both the freeway level and the local street level.
- The relationship between enforcement strategy, enforcement effort, and enforcement effectiveness in an urban setting.
- The optimal routing and balancing of commercial vehicle traffic on an urban freeway network to maximize road asset value and transportation efficiency.

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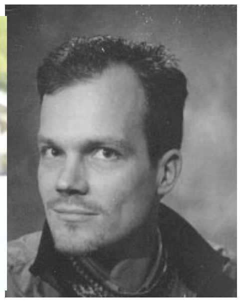
SUMMARY OF SESSION 4 : USE OF WIM DATA AS A TOOL FOR ENFORCEMENT

Dr. Chia-pei Chou obtained both Master and Ph.D. degrees from University of Texas at Austin, and specialized in highway and airport pavement design, management system, heavy vehicle sizes and weighs, weigh-in-motion application and the integration of commercial vehicle operation and ITS. She started her teaching career in 1989 and currently is a professor of Dept. of Civil Engineering of National Taiwan University and serves as the Director of Centre for International Academic Exchanges of NTU.



A graduate in Electrical Engineering from the University of Twente, he joined the Traffic and Transport Division of the National Police Agency as a technology advisor in 1994. Since 1999 he is project manager of the WIM-Hand project at the Road and Hydraulic Engineering Division (DWW) of the Dutch Ministry of Transport, Public Works and Water Management. The DWW is a partner in the REMOVE project.

C. P. CHOU
National Taiwan University
ROC

H. VAN LOO
Road and Hydraulic Engineering Institute,
Delft, The Netherlands

Presentations

During this session five papers were presented. The first presentation by Hans van Loo described the European Remove project. The goal of this project is the harmonisation of the enforcement of overloading in the EU and the introduction of WIM-systems. The project has a broad consortium consisting of enforcement agencies, road management departments, WIM specialist and the Transport industry. Difference with previous international WIM projects (COST 323 and WAVE) is that the Remove project is user driven instead of technology driven. The second presentation by Daniel Stanczyk, focussed on the ongoing preparation for a network of WIM and average speed systems in France. Using the WIM-systems as a pre-selection tool for legal (static) weighing results in an important increase in the efficiency of the overload controls. The accuracy of WIM-systems from two manufactures were tested in order to be able to set realistic specifications. The accuracy showed to be class D(20) for both systems according to COST 323. The European call for tender for the first 10 systems started in September 2004 and is still running. In the third presentation Ronald Henny showed the vehicle for dynamic calibration of a multiple sensor WIM-system in The Netherlands. The vehicle uses strain gauges and accellerometers for the measurement of the dynamic axle loads. The vehicle was built in cooperation with a notified body, Kalibra who also calibrate static weigh bridges. As a result the Ministry of Transport only paid for the WIM-related measurement equipment and the vehicle is operated by qualified personnel. The fourth presentation by Victor Dolcemascolo concerned the preparation of a multiple sensor WIM test site for automatic overload control in France. The systems will consist of 16 rows of piezoceramic sensors, two transverse location sensors, a temperature sensor and a digital camera. 13km down stream of the MSWIM a low speed WIM-system is built on a parking lot.

The final presentation by Tom Der was on commercial vehicle loading in an urban environment. A single load cell scale type WIM-system (IRD) is used to monitor the traffic on a urban road in the city of Saskatoon, Canada. Overviews were made of the distribution of overloaded vehicle by truck class, time of day, day of the week and by type of overloading (GVW and axle loads). These overviews combined with pictures from the overloaded trucks are used as a tool to improve effectiveness of enforcement efforts.

Questions and Answers :

A selection of the questions and answers after the presentation:
Q: Are the results of the Remove project available?
A: Not yet since the project is only half way but the results will be made public through the internet and the WIM-user network.

Q: What are the experiences in Canada with confronting transport companies with their overloading problem using registrations from the WIM-VID system.
A: No experience yet since this has not been operational procedure yet. However a similar operation in The Netherlands has been very successful for many years.

Q: What are the privacy constraints for the Canadian WIM-VID system?
A: There is permission to store the registrations (WIM-measurements + video image) for 1 month.

Q: Why dig such a big hole to install a load cell system when accurate piezoquartz sensors are available?
A: There are a number of reasons: a load cell scale WIM-system is less sensitive to vehicle dynamics than a single sensor piezo strip WIM-system, load cells have a long durability and finally load cells are more or less the standard.

Q: What is the improvement of using the calibration truck to perform dynamic calibration compared to 'normal' static calibration?
A1: No results yet since the first calibration will be done in March 2005. However the dynamic calibration will be part of the calibration procedure which will be part of the certification of a WIM-system for direct enforcement.
A2: Without dynamic calibration the spatial repeatability will result in a bias in the calibration of the individual sensors.

Q: Why are only piezoceramic sensors used in the French MSWIM test site?
A: No final choice on the type of WIM-sensor has been made.

SESSION 5 :

APPLICATION OF WIM TO INFRASTRUCTURES (PAVEMENTS AND BRIDGES)

Chairperson: Lily Poulikakos
Co-chair: Arturo González

MONITORING TRAFFIC LOADS AND PAVEMENT DEFORMATIONS ON A SWISS MOTORWAY



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Abstract
On the occasion of rehabilitating the heavily trafficked Swiss motorway a long-term pavement performance study was initiated in 1998. For this purpose an in-situ measurement station was installed to record traffic loads (Weigh–In–Motion), vertical deformations and temperatures within the cross section of the pavement. The paper presents the traffic loads and their development between 1998 and 2003 as well as the deformation response under traffic measured with Differential Deflection Measurement (DDM) devices.

Keywords: Weigh-in-Motion, Long Term Pavement Performance (LTPP).

Résumé
A l'occasion de la réfection de l'autoroute à fort trafic une étude sur les performances à long terme des revêtement à été lancée en 1998. A cet effet, une station de mesure in situ a été installée pour enregistrer les charges du trafic (Weigh–In–Motion), les déformations verticales et les températures sur la section du revêtement. Cet article présente les charges du trafic enregistrées et leur développement entre 1998 et 2003 ainsi que les réponses de déformation sous trafic mesurées à l'aide de déflectomètres DDM (Differential Deflection Measurement).

Mots-clés: Pesage en Mouvement, Performances à Long Terme des Chaussées (LTPP).

瑞士高速公路交通載重及鋪面破壞之監測

摘要：
1998 年因瑞士一條高交通量高速公路之重建，開始了一項長期鋪面績效 (Long term Pavement Performance) 研究計畫，其並設置一現地量測站，除以動態地磅（Weigh-in-Motion, WIM） 量測車輛載重外，並紀錄鋪面之垂直變形及沿鋪面深度之溫度變化情形。本研究主要討論 1998 至 2003 年間所記錄之交通載重，以及以微分撓度量測 (Differential Deflection Measurement, DDM) 設備所紀錄在載重下之鋪面變形反應資料。

關鍵字：**動態地磅、長期鋪面績效**

1. Introduction

With the increasing number of vehicles on highways and increasing axle loads the need for durable “zero maintenance roads” with high bearing capacity increases. In most cases, traffic monitoring equipment records only the number of vehicles on a particular highway section. There is still insufficient information regarding axle loads and their impact on the pavement under real climatic conditions. This information is needed to provide a basis for the development and optimization of pavement-dimensioning models. Such information is also required for the development of materials and new structural concepts.

Within the scope of rehabilitating the heavily traveled Swiss motorway A1 between Zürich and Bern, in 1998 a long-term in-situ measurement system was installed to record amount and frequency of traffic loads, the numbers and type of vehicles as well as pavement temperatures and vertical deformations within the cross section of the pavement. The aim of the still ongoing EMPA project is to collect and evaluate relevant data for improving the system properties and service life of roads. Hence, it was decided to include this section in the European cooperative project “Eureka Logchain Footprint” and therefore to extend and upgrade the measurement station. (Poulikakos et al., 2005). Thus, this test section will contribute to improve not only the basis for design and rehabilitation of future pavements in Switzerland but also the long-term field performance and robustness of in-situ monitoring devices.

2. Location

The current test section is approximately 250 m long and located on the A1 national motorway near Lenzburg between Zurich and Bern in Switzerland. The measurement systems were installed in 1998 on the slow lane towards Bern (Raab et al., 2003).

The locations of the individual measuring devices for weigh-in-motion (WIM), temperature (T) and deformation (D1 to D3 and W1), were chosen in a way to minimize the cable lengths and the influence of the devices on each other. An overview of all measuring locations is given in Figure 1. The deformation measurement devices consisted of two different displacement transducers systems D1...D3 Differential Deflection Measurement (DDM) and a magnetostrictive deformation measurement device W1 which were lined up at short distance in the right wheel track. This paper concentrates on the results of the D1…D3 measurement devices. A discussion between the two types of deformation measurement devices is presented in (Raab et al., 2003, Anderegg et al., 2000, Anderegg et al., 2002).

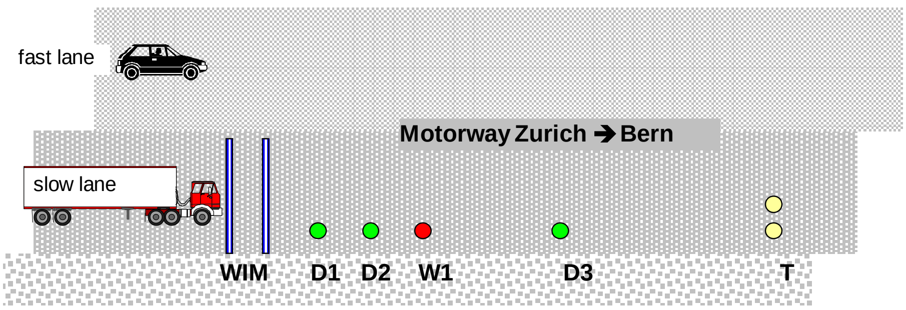


Figure 1- Overview of all Measuring Points on the Test Site on the A1 Motorway

Figure 2 depicts schematically the location of the deformation and temperature measuring devices in the individual layers of the pavement. These layers consist of a 4cm thick stone mastic SMA 11 S wearing course, a 8cm thick asphalt concrete HMT 22 H upper base course, a 10cm thick asphalt concrete HMT 32 H lower base course and a 10cm thick asphalt concrete HMF 22 S subbase.

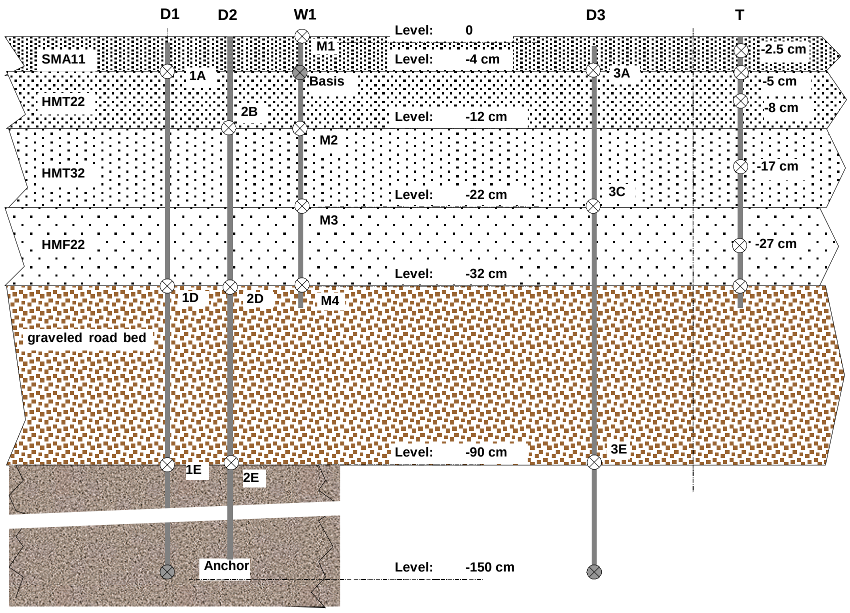


Figure 2 - Location of the Measuring Devices in the Individual Pavement Layers

3. WIM-Measurements

Monitoring of vehicle weight, the axle loads and frequency of passing vehicles is conducted by a WIM (weigh-in-motion) system that consists primarily of two load cells with piezo-electric quartz sensors-LINEAS made by Kistler Company. The data are collected by an on-site computer and transferred via modem for evaluation purposes. From the characteristic load/time signal, the vehicle type is determined. In addition, the load equivalency factor with respect to the equivalent single axle load (ESAL) of 8.16kN is calculated.

Figure 3 presents the average daily distribution of heavy vehicles over the years 2000 and 2002. Weekends and public holidays are not taken into consideration. According to the data evaluation presented in Figure 3 for the year 2000, average number of heavy vehicles (> 8t) per hour ranged between 120 and 140, extending up to 230 heavy vehicles during rush hours. In the year 2002 the number of heavy vehicles increases to an average of more than 135 vehicles (> 3.5t) or even 195 vehicles when neglecting night hours (9:00pm to 5:00am). The traffic volume with more than 200 heavy vehicles per hour starts in the early morning between 6am and 7am (where we find the peak value of 275 vehicles) and is distributed quite equally during the morning (average of nearly 250 vehicles). After a slight decrease of traffic during lunch time (12:00am to 2:00pm) the traffic volume decreases continuously in the course of the afternoon and evening (from about 230 vehicles between 2:00pm and 3:00pm to about 50 vehicles between 7:00pm and 8:00pm). During the night (10:00pm to 4:00am) the system measures an average of only 15 vehicles per hour. In the year 2001 the mode of data collection was changed from monitoring vehicles > 8t to monitoring vehicles > 3.5t. For this reason it is not possible to evaluate the total increase of heavy vehicles between the year 2000 and the year 2002.

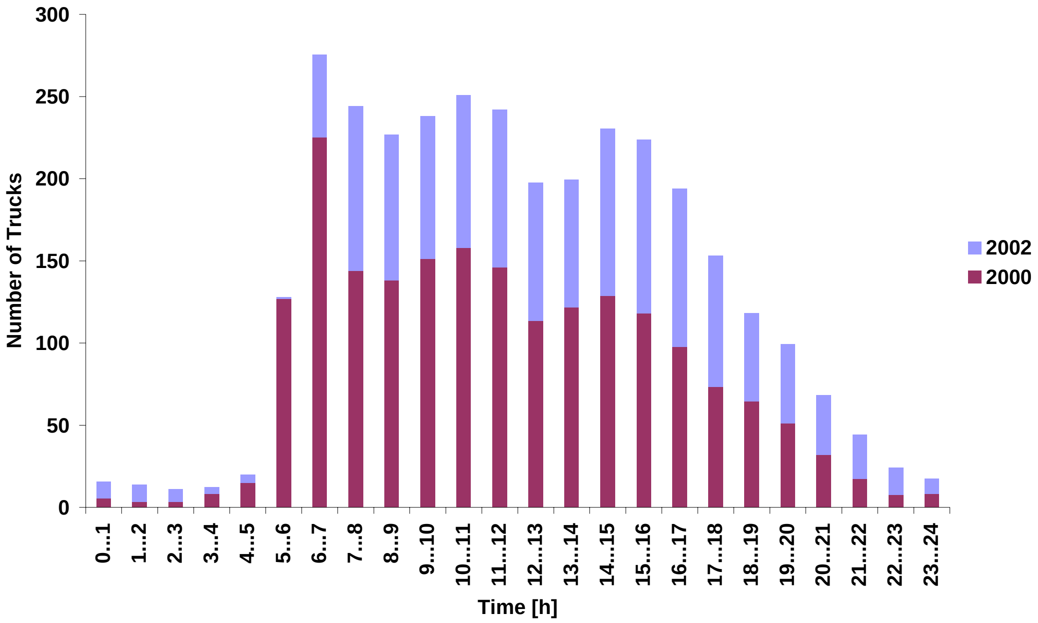


Figure 3 - Daily Distribution of Heavy Trucks over the Years 2000 and 2002 (2000 Trucks > 8t; 2002 Trucks > 3.5t)

As shown in Figure 4 the WIM data for single days were compiled in 3D-histograms which were considered very suitable statistical fingerprints of the load history. In particular, the surface plots of these 3D-histograms enable a direct comparison between WIM data (loads [KN]) and deformation data (deformation [mm] as determined by DDM).

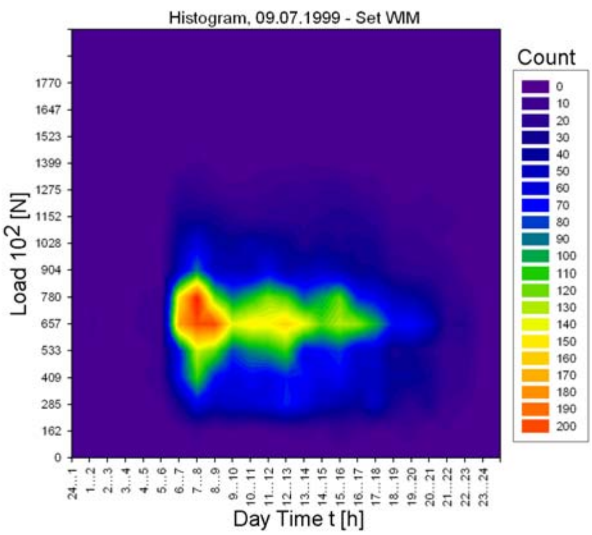


Figure 4- Example of a Daily WIM-3D-Histogram for Heavy Vehicles > 8t (09 July 1999)

4. Deformation Measurements

In order to determine the structural impact of vehicles on the different layers of the pavement by measuring the relative vertical deformations of the pavement at various depths, a measurement system consisting of a number of Differential Deflection Measurement (DDM) devices D1 to D3 was installed. These inductive measurement devices consist of a guide tube holding several LVDTs. The guide tube is solidly anchored in a depth of 1.5 m (Figure 2). The different LVDTs are fixed on the guide tube at different depths of the pavement. The movable iron cores of the LVDTs are attached to the measurement points in the pavement with spring clamps in order to measure the relative displacements between their target and the anchor (Figure 5). The devices D1 to D3 are based on the Multi Depth Deflectometer (MDD) system, which was developed in 1980 by CSIR in South Africa and installed in a re-designed and modified version by a Portuguese firm. Unfortunately, the installation of the system, especially the drilling of the anchor turned out to be rather difficult. The sealing and frost protection of the sensors proofed to be an even more critical point: After only one winter, the first sensor D1 had to be replaced. Due to the harsh environmental conditions, which resulted in a deterioration of the whole system, the evaluation of a new measurement device was necessary.

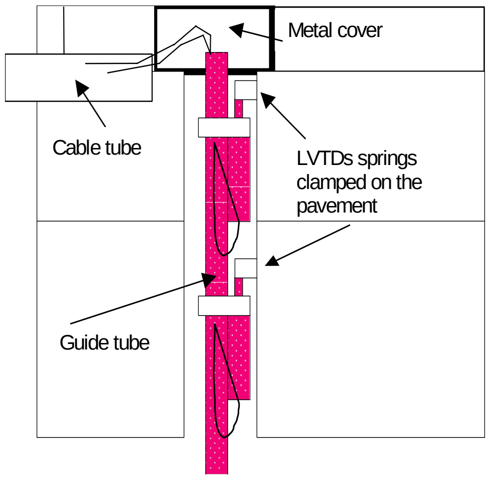


Figure 5 - Schematic of the DDM Measurement Devices D1 to D3

As described for the WIM data in section 3, the deformation measurements from the inductive system were plotted in 3D-histograms (Partl, 2003). Figure 6 shows as a typical example the surface plot corresponding to Figure 4. The three peaks of Figure 4 can be recognized in Figure 6. However, it is interesting to note, that all deformation peaks have the same intensity whereas the first load peak is clearly dominant. This can be partly explained by the increase of temperature during a summer day but also in the discrepancy between the >8t and >3.5t vehicles during the day as shown in Figure 3. It clearly confirms that the heavy vehicles between 3.5t and 8t are significantly contributing to the road deformations and must not be neglected.

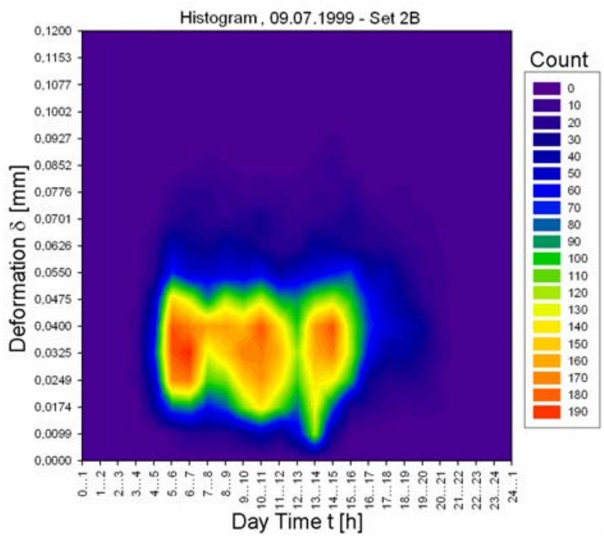


Figure 6 - Example of a Daily Deformation-3D-Histogram of D2 in 12cm Pavement Depth (09 July 1999)

5. Comparison of Daily Distribution of Deformation and Load (WIM)

Figure 6 and Figure 7 depict the deformation-3D- histograms for the LVDT at D2 in12cm depth for three different spring or summer days. The deformation histograms all clearly show the 3 peaks (see Figure 4) at 6:00…7:00am, 10:00…11:00am and 2:00…3:00pm. In the histogram from 17. August 2000 the peak at 2:00…3:00pm is less distinct, but still visible.

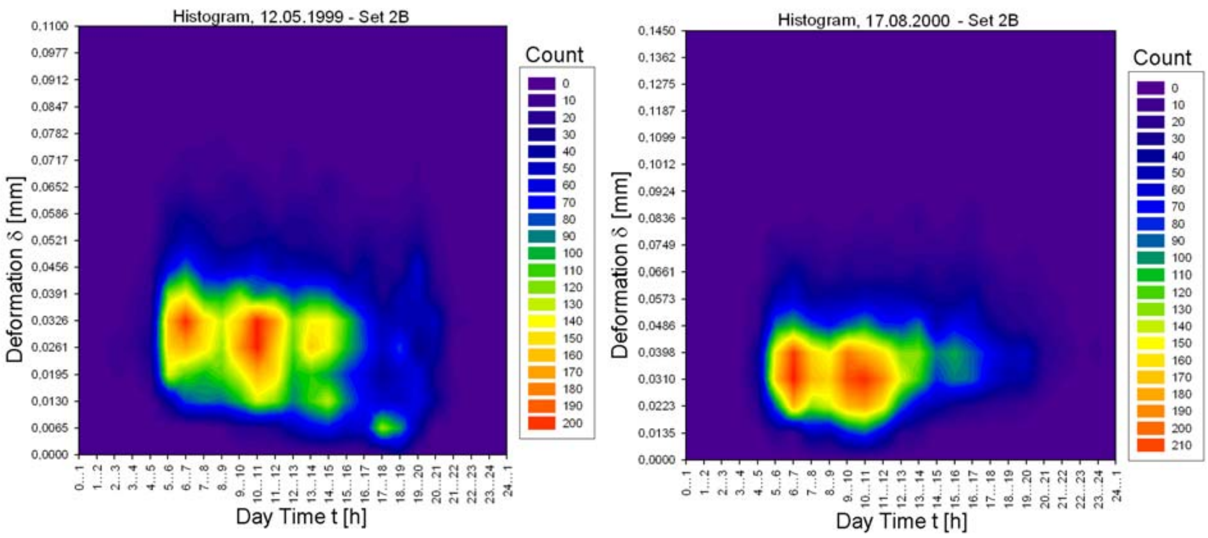


Figure 7 - Deformation-3D-Histograms of D2 in 12cm Pavement Depth for 12 May 1999 (Left) and 17 August 2000 (Right); Note that the Scale of y-Axis Are Slightly Different

The deformation histograms from winter days may obviously be different (Figure 8). The histogram from 8. December 1999 (Figure 8, top, left) shows the first two peaks, but the one at

2:00pm is missing. This result is confirmed by the WIM-3D-histogram (Figure 8, bottom, left) where also the third peak between 2:00…3:00pm is almost not existent. The opposite can be stated for the 22. January 1999 histogram (Figure 8, top, right): Here only the peak at 2:00pm is clearly visible whereas the peak at 6:00am is only faintly detectable. In this case the weather appears to play an important role. The temperature measurement for this day (see Figure 8, bottom, right) with temperatures below 0°C in the morning and increasing temperatures in the afternoon leads to the conclusion that the motorway might have been blocked by ice and snow in the morning and traffic was getting back to normal only after a thaw period in the afternoon.

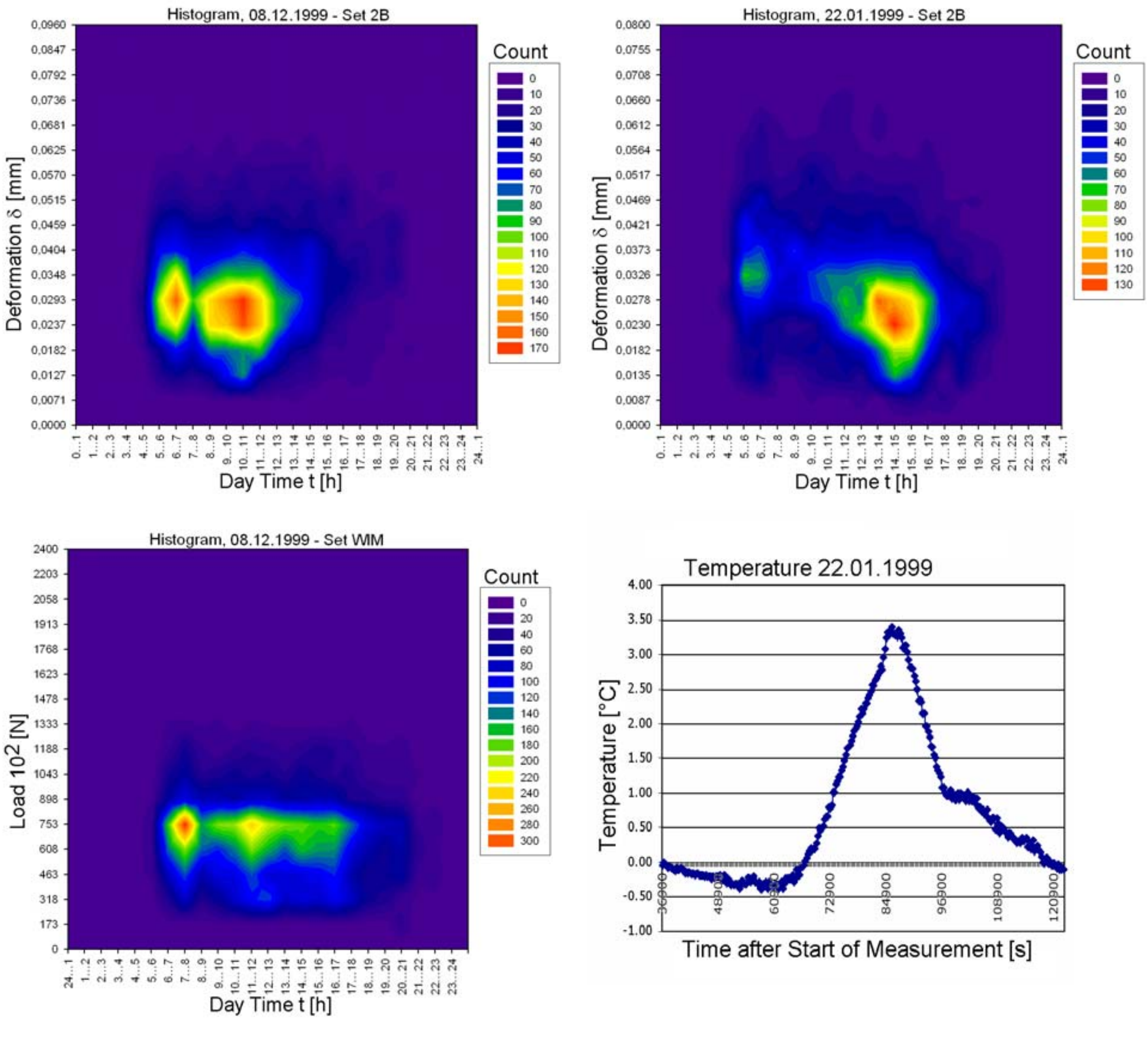


Figure 8 - Deformation-3D-Histograms of D2 in 12cm Pavement Depth for 2 Different Winter Days; WIM-3D-Histogram for 8 December 1999 (Heavy Vehicles > 8t) and Temperature for the 22. January 1999 in 2cm Depth of the Pavement (Note that the colour codes for the counts are different)

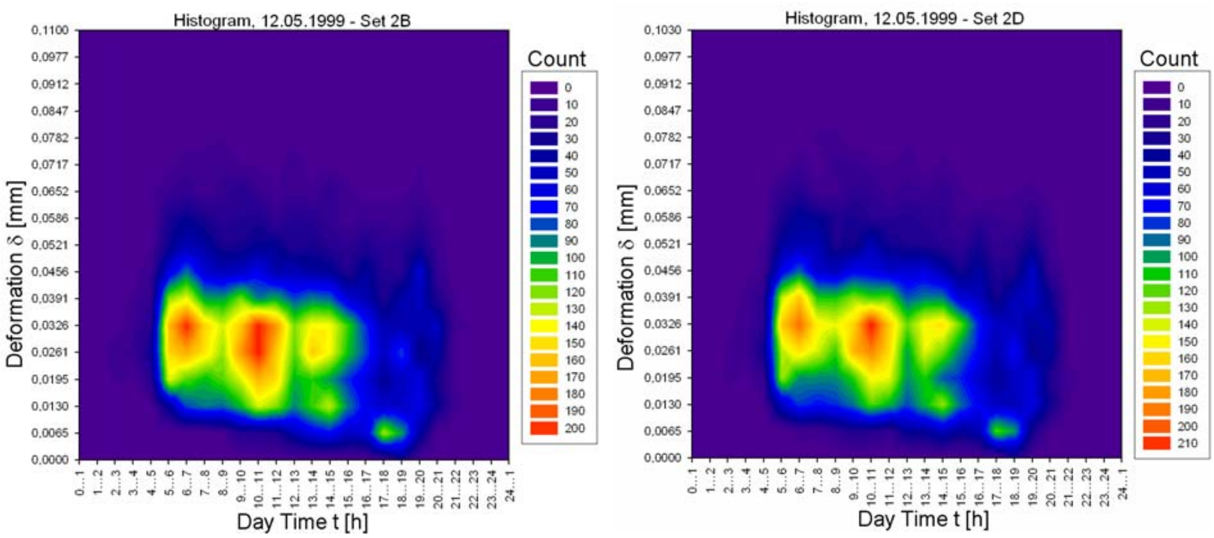
It is important to note that all deformation peaks appear in the lower third of the statistically evaluated deformation range. This means that the test site experienced a great number of small deformations but only few big ones. Therefore pavement deformation is caused not only by heavy loads, but even more by small loads. A comparison with the WIM histograms confirms this finding. The difficulty with the WIM data is that only vehicles >8t were taken into consideration during the DDM measurements before 2001. The comparison between deformation and WIM histograms states the similarity between the first peaks at 6:00am, whereas the following peaks are less clearly visible in the WIM histograms. The peak at 6:00am therefore seems to be caused by vehicles >8t. The fact that the deformation is not only caused by heavy vehicles (>8t) already led to a change in the recording of the WIM data, where since 2001 all vehicles >3.5t are monitored.

6. Deformation in Different Pavement Depths

As shown in Figure 9 the signals of D2 coming from the LVDT sensors 2B, 2D and 2E in 12cm, 32cm and 90cm depths of the pavement are similar and vary mainly in range, shape and intensity of the peaks.

A comparison between sensors 2B and 2D reveals their similarity in range and shape. Only the intensity of the signal differs according to their position in the depth of the pavement.

For sensor 2E in 90cm depth the differences are more clearly visible, the deformations of this sensor are about 80% smaller (note significantly different scale on y-axis in Figure 9) and the peaks are shifted in the direction of the time scale.



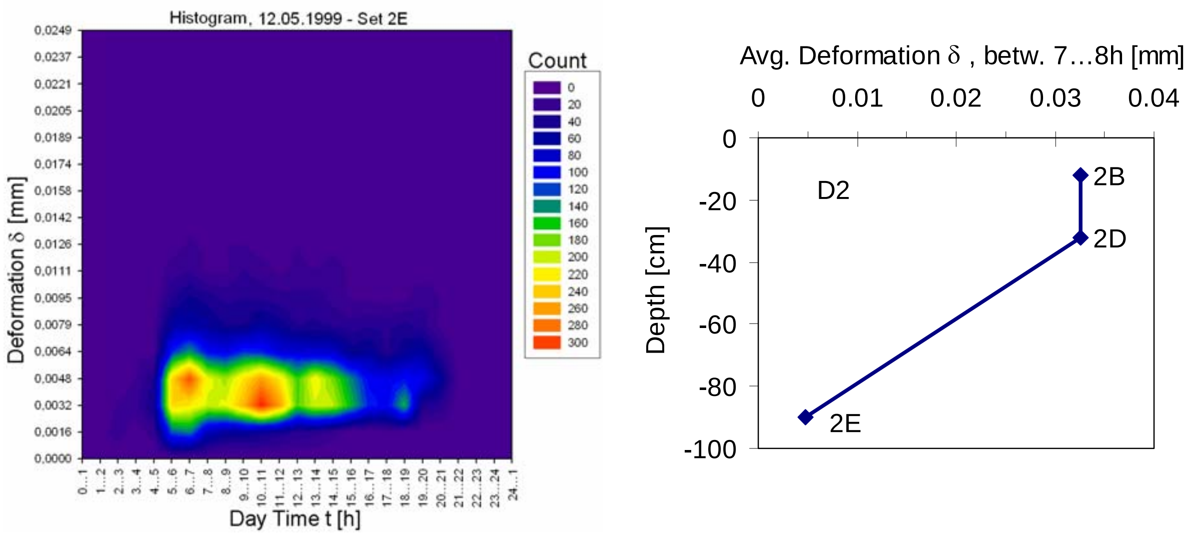


Figure 9 - Deformation-3D-Histograms of D2 for the LVDT Sensors 2B, 2D and 2E in 12cm, 32cm and 90cm Pavement Depth and Average Deformation between 7:00…8:00am vs. Depth

7. Temperature Influence on Deformation

In order to evaluate the influence of the temperature on the deformation, the deformation data for one sensor from a 3D-histogram were summed up to a normal 2D-histogram (as an example Figure 10 shows the sensor 2B of D2).

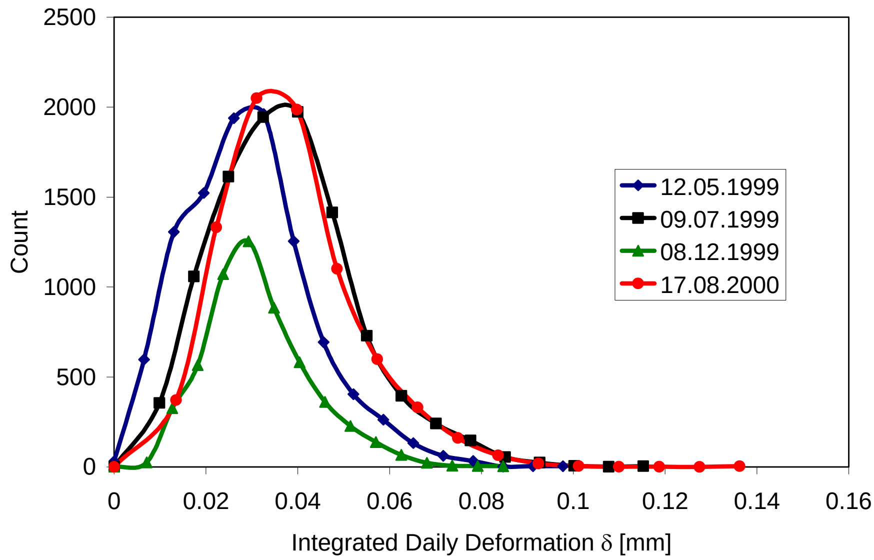


Figure 10 - Comparison of Summed Up 2D-Histograms for the Sensors 2B

The fact that the peaks of the warmer days are higher than the ones of the colder days show that the deformations are smaller in winter, which is found to be in harmony with the theory.

When plotting the peak values of deformation and temperature into a XY diagram (Figure 11), it can be shown by simple linear regression analysis that the susceptibility to deformation increases with increasing temperature, which is in agreement with general experience.

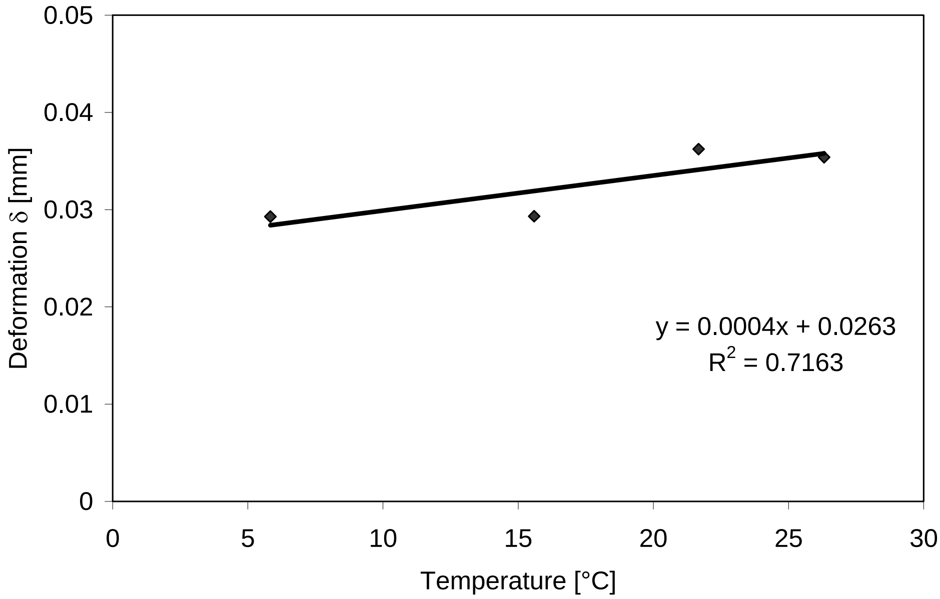


Figure 11 - Linear Regression to Visualize General Trend between Peak Value of Integrated Daily Deformation for the Sensors 2B and Temperature

8. Conclusions and Further Steps

Higher traffic frequencies and higher axle loads in conjunction with seasonal temperature influences leads to increasing loads on highway pavements and the deterioration of the pavement accelerates. Better understanding of the deterioration process allows to optimize maintenance and to improve the durability of the pavement.

The method to evaluate WIM and deformation data in daily 3D-histograms proved to be a very useful tool for a better understanding of the pavement behaviour. The comparison between WIM and deformation histograms showed that not only heavy vehicles (>8t), but also lighter vehicles contribute to the pavement deterioration. A fact that was already taken into account by changing the evaluation mode of the WIM system from >8t to >3.5t. Although the DDM deformation device, when still intact, seemed to give some useful information about the pavement response, the in-situ measurement system still needs considerable technical improvement. A next step in that direction will be performed in the up-dating of the measurement system on this section for the Eureka Logchain Footprint project.

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SIMPLIFIED SITE SPECIFIC MODELS FOR DETERMINATION OF CHARACTERISTIC TRAFFIC LOAD EFFECTS FOR BRIDGES

MSc, PhD. He is a postdoctoral fellow under the Marie Curie Development Host Fellowship and he is mainly working on probabilistic-based assessment of bridges using recorded traffic data.

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Abstract
The traffic load models given in codes are intentionally made conservative since they are valid for a wide range of bridge types and loading conditions. Today, the same bridge assessment principles are applied equally to bridges carrying dense traffic of heavily loaded trucks and those carrying sparse traffic of lighter trucks. In recent years, simulation techniques, using WIM, have been used to predict the characteristic traffic load effects on bridges. However, the techniques are complex and require a good knowledge of statistical theory. This work presents a simplified site-specific traffic load model that generates comparable load effects to the corresponding results from a full simulation. The simplified model can be employed by practicing engineers for bridge assessment.

Keywords: Bridge, Simplified Model, Assessment, Site-Specific, WIM, Weigh-In-Motion, Monte Carlo Simulation**.**

Résumé
Les modèles de charge de trafic des codes sont délibérément conservatifs puisqu'ils doivent s'appliquer à un vaste ensemble de types de ponts et de conditions de trafic. Aujourd'hui les mêmes principes de vérification de ponts s'appliquent aux ouvrages supportant des trafic denses et des poids lourds fortement chargés et des faibles trafic avec des poids lourds peu chargés. Dans les années récentes, des techniques de simulation utilisant des données du pesage en marche ont été appliquées pour prédire les valeurs caractéristiques des sollicitations du trafic sur les ponts. Cependant ces techniques sont complexes et exigent une bonne connaissance des théories statistiques. Ce travail présente un modèle simplifié de charges de trafic spécifique au site qui engendre des sollicitations comparables à celles d'une simulation complète. Le modèle simplifié peut être utilisé par des ingénieurs et praticiens pour une vérification de pont.

Mots-clés: Pont, Modèle Simplifié, Vérification, Spécifique au Site, Pesage en Marche, Simulation de Monte-Carlo.

定義橋梁特殊載重效應之特定場站簡化模式

摘要：
交通載重模式在應用上一直是偏向保守，因為需適用於不同橋梁形式及載重狀況之分析。目前，不論是交通量大、載重量大的橋梁或是交通量分散、載重小之橋梁都採用同樣的橋梁評估準則。近年來，應用動態地磅 (Weigh-In-Motion, WIM) 之模擬技術已可用於預測橋梁上之載重效應。然而，上述方法相當複雜而且需要豐富之統計理論知識。本文主要內容為說明利用一種簡化之特定場站交通載重模式，其可經由比擬之模擬獲得與結果相對應之載重效用資料。工程師並可採用上述簡化模式進行橋梁評估。

關鍵字：橋梁、簡化模式、評估、特定場站、動態地磅、蒙地卡羅模擬

1. Introduction

The traffic load models given in codes of practice are purposely made conservative in order to be valid for a wide range of bridge types and loading conditions and because the marginal cost of providing additional capacity is low. Load models for bridge assessment tend to be less conservative. However, in most countries the same bridge assessment principles are applied equally to bridges carrying dense traffic with heavily loaded trucks and those carrying sparse traffic with lighter trucks. In some cases bridges are judged to be structurally deficient according to these conservative load models. Therefore, an approach, which considers the traffic weight and volume statistics for a specific bridge site provides a more accurate representation of the actual loading conditions on the bridge considered and can save the costs associated with unnecessary bridge rehabilitation and replacement.

WIM systems are widely available today to provide unbiased vehicle data. In recent years, increasingly sophisticated probabilistic analyses have been preformed using WIM data resulting in a more accurate knowledge of the actual traffic loading on bridges. Considerable attention has been given to the process of extrapolating the maximum traffic load effects, simulated using WIM data, which is valid provided that there is no change in the underlying traffic weight or density profile. In the content of bridge assessment, ongoing monitoring of WIM data can provide reassurance that no such change has occurred. The prediction of these maximum load effects can be performed utilizing a wide range of simulation and extrapolation techniques. The results have shown that there is a significant site dependence of characteristic traffic load effects. This is counter to the principle that is applied in many countries today where the same bridge assessment rules are used for bridges carrying dense traffic with heavily loaded trucks and those carrying sparse traffic with lighter trucks.

The methods used for the calculation of characteristic traffic load effects are complex and require a good knowledge of statistical theory. In this work, the site traffic dependence of extrapolated load effects are investigated. A simplified model is developed which aims to reproduce similar critical loading events from knowledge of the site-specific traffic characteristics without having to perform a full Monte Carlo simulation. It should be emphasized that the simplified model is site-specific, that is, the parameters for the model are directly related to traffic data specific to the site considered. The investigation has been limited to the case of mid-span moment and end shear in simply supported bridges with spans ranging from 15 to 35 meters. The bridges are assumed to have two traffic lanes, one in each direction. The new method is validated using WIM data from four different sites. From these, load effects corresponding to different return periods are calculated. The results of the Monte Carlo simulation are then compared to the results obtained from the simplified model.

2. WIM Data

The WIM data sets used in the present work were recorded at four different sites. The first three data sets were recorded on three different Highways in the Netherlands while the fourth was recorded on a Highway in France. The sites are referred to here as Site 1, Site 2, Site 3 and Site 4, respectively. In all cases, the Highways are dual carriageway with three to four traffic lanes in each direction. The data was collected on the outer most (slower) lanes in each direction. Only vehicles weighing at least 3.5 tonnes (i.e., only trucks) were registered. The measurement locations and periods are given in Table 1.

Table 1 – Measurement locations and periods

Denotation	Highway	Site location	Measurement Period
Site 1	R04	Amsterdam	6/10 to 19/10, 2003
Site 2	R12	Utrecht	6/10 to 19/10, 2003
Site 3	R16	Dordrecht	6/10 to 19/10, 2003
Site 4	A1	Ressons	9/9 to 14/9, 1996

The data were recorded continuously for different periods as can be seen in the table. Figure 1 illustrates the distributions of trucks by number of axles in each sites and direction. While the dominant recorded trucks, in all cases, have six or less axles, there are a small but important number of trucks having more than that. The vast majority of the 5-axle trucks from all sites are articulated trucks. Most of the vehicles recorded with more than five axles seem to be trucks with a tractor unit pulling a trailer.

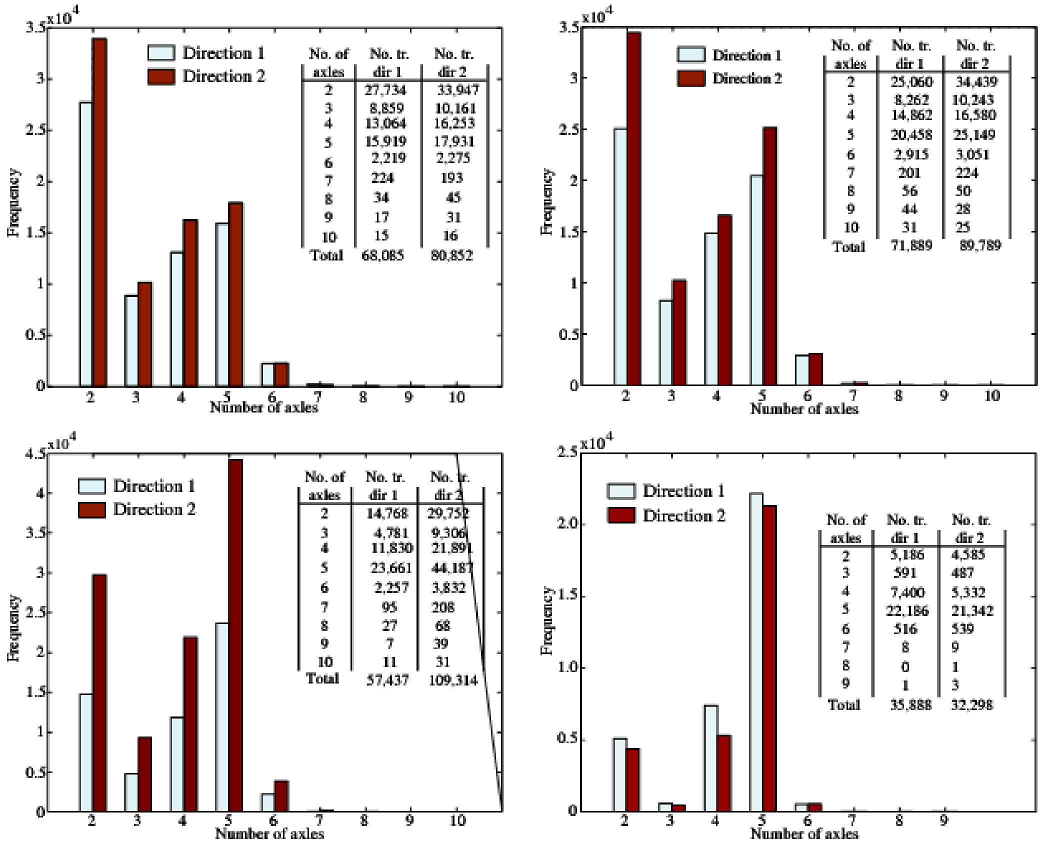


Figure 1 - Comparison of Measured Distributions of Truck

Figure 2 provides a comparison of the Gross Vehicle Weight (GVW) distributions determined using the WIM data measured at the different sites. Clearly, the histograms have two main peaks representing two different truck populations. It is generally assumed that the first part of such histograms represents small trucks and unloaded large trucks while the second part represents fully loaded large trucks. As can be seen in the figure the measured GVW histograms for Site 1–Site 3 (from the Netherlands in 2003) have heavier right tails than that for Site 4 (from France in 1996).

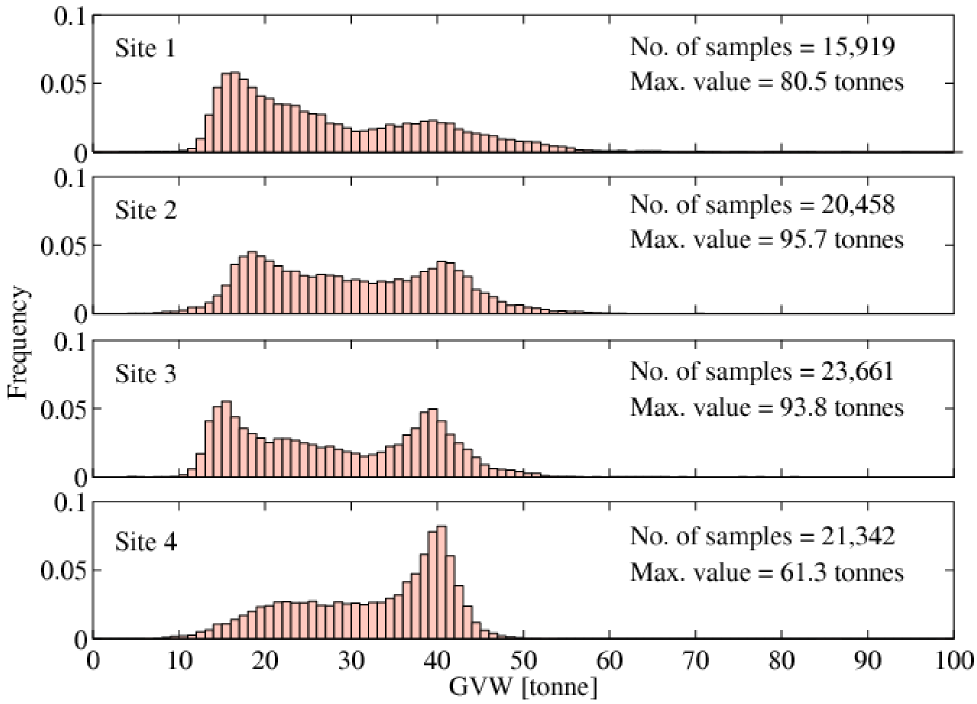


Figure 2 - Comparison of Measured distributions of GVW of 5-axle Trucks. Direction 1

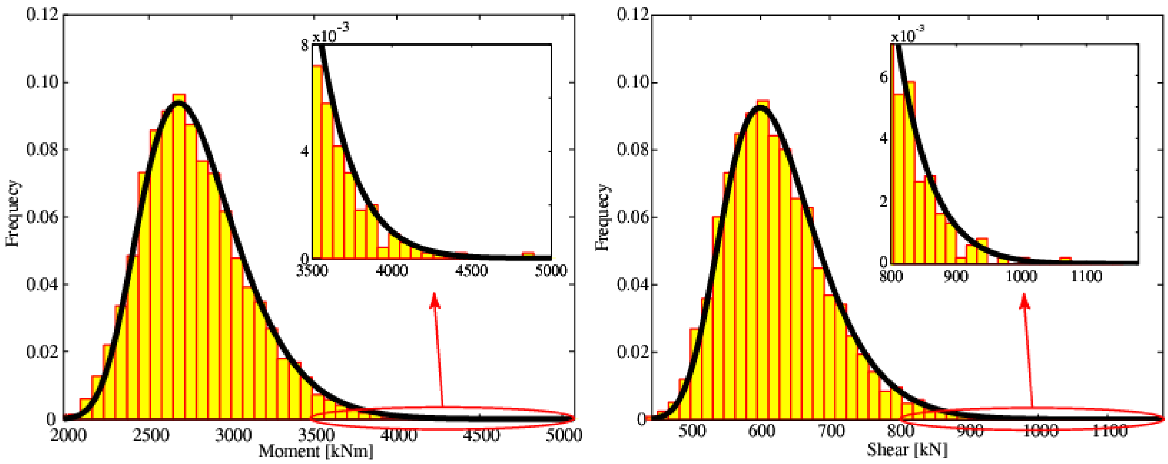
3. Simulations

Generally, the Monte Carlo simulation technique is utilized in order to determine the characteristic values of different traffic load effects using WIM data. Histograms for different traffic characteristics are usually fitted with appropriate probability distribution functions which are then used for the simulations. There are usually very few but very important data points in the right hand tails of the GVW histograms. Therefore, parametric probability distribution functions which are usually obtained by fitting to the entire histograms of GVW, can give a poor description of the histogram tails. (Getachew and O'Brien, 2004) have shown that the calculated characteristic load effects are very sensitive to the model used to represent the tail for the GVW distributions. They propose a semi-parametric model to fit the distribution of the GVW. This model effectively generalizes the trend in the tail region of the GVW distribution while reverting to a direct use of the histogram when there is sufficient data for a clear trend to be evident. The semi-parametric distribution is used to represent the GVW histograms for the simulations in the present work.

Earlier studies have shown that, for short and medium span bridges, free-flowing traffic with two trucks present simultaneously on the bridge, gives the critical loading events, see e.g. (Nowak ,1993b) and (Flint and Jacob, 1996). For this study two trucks meeting on the bridge is assumed to represent the critical loading scenarios. In order to simulate the truck meeting events, an artificial traffic stream, which represents four weeks of traffic flow, is first simulated using the recorded data sets. The meeting events are defined as events involving the presence of at least one axle of a truck in each direction on the bridge simultaneously. The number of truck meeting events for bridges with spans of 15–35 meters is determined for each site. The load effects, the mid-span moment and end shear for simply supported bridges of different lengths, are calculated using the influence line and superposing the effects of each axle of each truck.

4. Load Effect Extrapolation

Using the simulated data sets and the information on the number of truck meeting events for each site, the load effects are calculated for bridge spans of 15, 20, 25, 30 and 35 meters. The calculated load effect data sets are fitted to a Generalized Extreme Value (GEV) distribution, (Castillo, 1987); (Jacob, 1991); (Coles, 2001). As an example, Figure 3 illustrates the density functions of the GEV model fitted to the calculated load effects for bridge span of 20 meters and for Site 2.

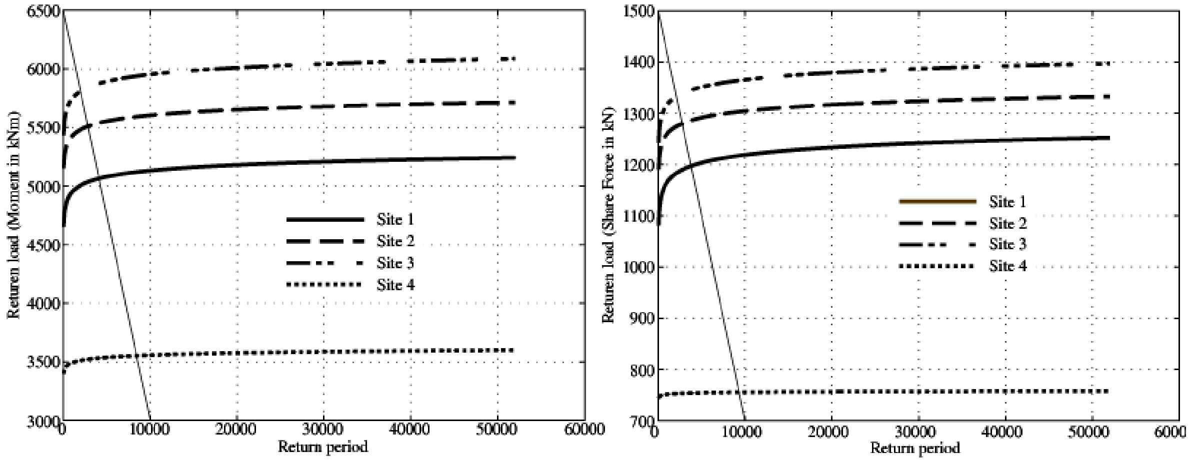


(a) Daily maximum mid-span moment

(b) Daily maximum end shear

Figure 3 - GEV Pdf's Fitted to the Daily Maximum Load Effect Histograms Obtained from the Simulation, L = 20m. The Inserted Figures Show the Magnified Sections of the Tails.

As can be seen in the figure the histograms of the load effects are well described by the GEV model. Good agreements are also observed between the histograms of the load effects and the GEV models for the other studied bridge spans and sites. The characteristic extreme load effect values for different return periods are calculated using the GEV model for each of the four sites and for each of the bridge spans considered. As an example, these values calculated for different return periods and for a bridge span of 20 meters, are illustrated in Figure 4. As seen from the figure, the extrapolated values for the both load effects, are in descending order from Site 3, Site 2, Site 1 and Site 4.



(a) Mid-span moment (b) End shear

Figure 4 - Comparison of Estimated Return Loads versus Return Periods, Span = 20m

The characteristics of the trucks that are involved in the critical loading cases which give the daily maximum load effects are investigated. Five-axle trucks were found to dominate these loading scenarios. An investigation of the WIM data reveals that most vehicles with more than five axles are trucks with a tractor unit pulling a trailer while, as mentioned previously, the 5-axle trucks are mostly articulated lorries. The result is that, generally, the weight per unit length is greater for trucks with five axles than for those with more than five axles. Thus, the dominance of 5-axle trucks in the present study is not so surprising considering the lengths and the weights as well as the proportion of this truck types. Table 2 shows the extrapolated 1000 year load effects determined when the entire measured data and only data for 5-axle trucks are used as an input for the simulations, for Site 1 and Site 4.

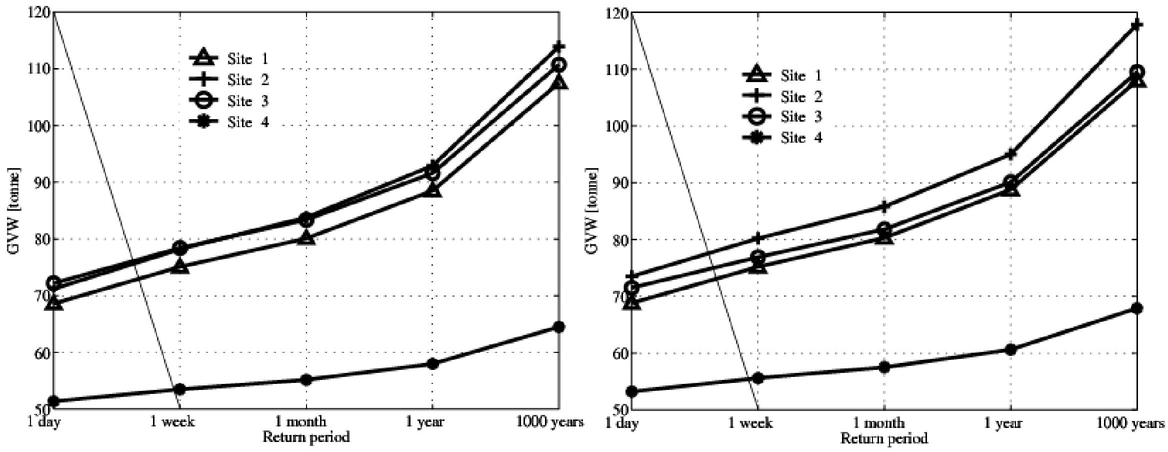
Table 2 – Comparison of the 1000 year return period load effects obtained when data for all trucks and data for only 5-axle trucks are used as an input for the full simulations.

Site	**L [m]**	**Moment [kNm]**			**Shear [kN]**		
		All tr.	5-axle tr.	Diff. [%]	All tr.	5-axle tr.	Diff. [%]
1	15	3573	3249	10.0	1124	1091	3.1
	20	5242	4769	9.9	1253	1208	3.7
	25	7021	6588	6.6	1299	1285	1.1
	30	9347	8559	9.2	1342	1315	2.0
	35	10592	9975	6.2	1390	1378	0.9
4	15	2162	2026	6.7	652	645	1.1
	20	3598	3551	1.3	758	774	-2.1
	25	5194	4752	9.3	824	820	0.5
	30	6311	6235	1.2	883	897	-1.6
	35	8330	7718	7.9	926	929	-0.2

The very low relative differences indicate that there is little loss of accuracy in most cases when only 5-axle trucks are considered. The differences for Site 1 are generally somewhat higher than for Site 4. This appears to be because the 5-axle trucks at Site 1 are not as dominant as at Site 4, as can be seen in Figure 1. For Site 4, it is observed that in some cases the extrapolated shear values from the simulations done when only 5-axle trucks are considered are greater than the corresponding values obtained from the simulation performed when all trucks are considered. These cases can only be explained as a consequence of the fitted GEV models which considered the entire data points (i.e. the daily maximum shears).

5. Simplified Model

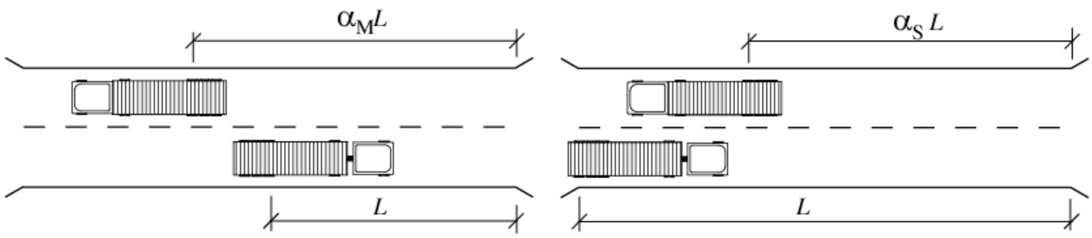
Applying the simulation technique described in the previous section requires not only a good knowledge of Extreme Value theory but is also time consuming and complex. A simplified model is described here that generates traffic load effects that can be used for bridge assessment without having to perform full simulations. As discussed in the previous section, the analysis of the daily maximum load effects obtained from the simulations reveals that 5-axle trucks, because of their lengths and weights, are dominant in the critical loading scenarios. The simplified model is therefore formulated with pairs of heavy 5-axle trucks placed at critical locations on the bridge. The load effects induced by these trucks are assumed to give a good estimate of the characteristic load effect values obtained from a full simulation. The simplified model is site-specific, i.e., the parameters for the model are directly related to WIM data measured at or near the site considered. The model is also expected to be accurate, robust and easily applied by practicing engineers. The idea is similar to that of Turkstra's Rule, Nowak (1993a), which is based on predicting the weights of trucks for different return periods and locating them at critical locations on the bridge. According to Turkstra's Rule, the resulting load effects correspond the characteristic values obtained from a full simulation. Figure 5 shows the characteristic GVW of trucks as a function of return period for both traffic directions and all sites.



(a) Direction 1 (a) Direction 2

Figure 5 - GVW of 5-axle Trucks versus Return Period

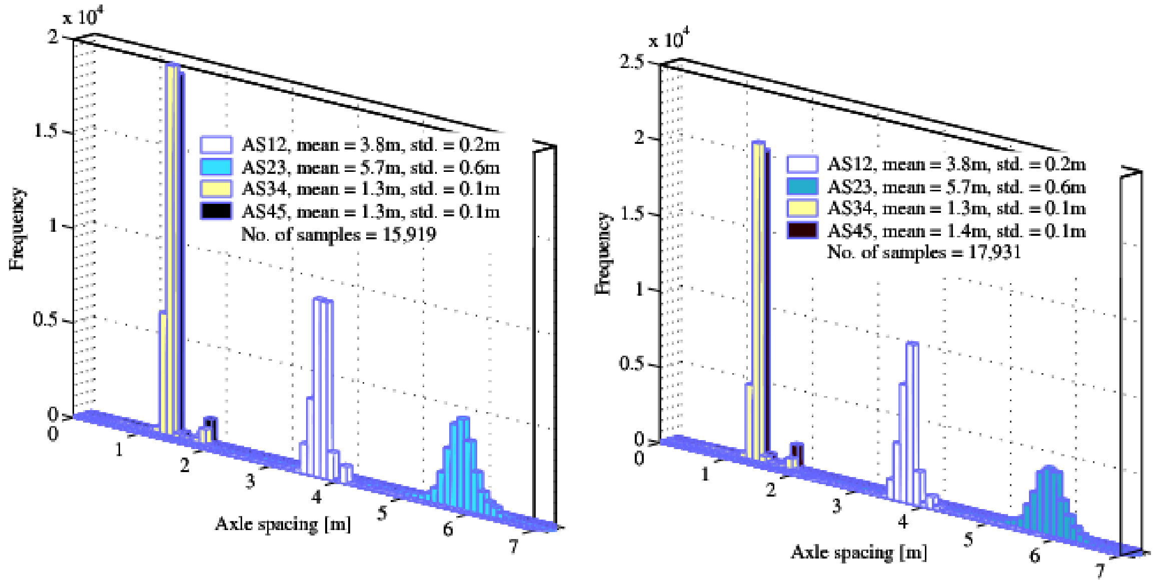
The 1000 year truck is that which is likely to occur only once in 1000 years. According to Turkstra's Rule, the 1000 year loading event can be assumed to involve the 1000 year truck meeting a more common truck—the one month or one week truck. While this is conservative and simplistic, it has the advantage of ease of application. With Turkstra's Rule, the trucks are assumed to meet at the critical point of the influence line which is clearly highly improbable. In this study, the second truck is assumed to be in a different location, not quite at the most critical point. The situation is different for the two load effects. For bending moment, the 3rd axle of the 1000 year truck is placed at the center while the 3rd axle of the 1 week truck is placed $\alpha_M L$ from the end as illustrated in Figure 6. For shear, the most critical location for the 1000 year truck is when the 5th axle has just entered the bridge. At this moment in time, the third axle of the 1 week truck is placed $\alpha_S L$ from the end. Values for $\alpha_M L$ and $\alpha_S L$ were chosen which gave a best fit to full simulation for all sites.



(a) Moment (b) Shear

Figure 6 - Description of the Simplified Model

Figure 7 illustrates the measured distribution of the axle spacing of the 5-axle trucks from Site 1.



(a) Direction 1 (a) Direction 2

Figure 7 - Measured Distributions of Axle Spacing for 5-axle Trucks Obtained from Site 1. ASij Indicate the Axle Spacing between the i-th and j-th Axles

The mean values and the standard deviations of the spacings, denoted as AS12 for the distance between the first and the second axle etc., are also shown in the figure. An investigation of the WIM data sets shows that, for 5-axle trucks, there is insignificant correlation between axle spacing and GVW. As the standard deviations of axle spacing are low, it is reasonable to assume mean values for axle spacing of the 5-axle truck in the simplified model. It should be mentioned that the difference between the mean values from different sites is insignificant.

6. Result Comparison

In this section the results obtained from the full simulations and the simplified model are compared. According to the Eurocode, CEN (2002), the characteristic value for traffic load effects has been defined for a return period of 1000 years, i.e., the value with a probability of exceedance of 10% in 100 years. The 1000 year load effects are determined from the distributions of the daily maximum load effects for each bridge length obtained from the full simulations. For the simplified model, single optimal values for $\alpha_M L$ and $\alpha_S L$ were sought that produced equivalent characteristic load effect values to the full simulations. According to this investigation, the optimal values for $\alpha_M L$ and $\alpha_S L$ are 0.63 and 0.42, respectively. The 1000 year load effects obtained from the full simulations and the corresponding values calculated from the simplified model are shown in Table 3.

Table 3 – Comparison of the 1000 year load effects obtained from the full simulations (FS) and the corresponding values obtained from the simplified model (SM) with $\alpha_M L = 0.63$ and $\alpha_S L = 0.42$

Site	L	Moment in kN			Shear in N		
	[m]	FS	SM	Diff. [\%]	FS	SM	Diff. [\%]
1	15	3573	3787	-5.7	1124	1137	-1.1
	20	5242	5601	-6.4	1253	1192	5.1
	25	7021	7578	-7.3	1299	1222	6.3
	30	9347	9592	-2.5	1342	1402	-4.3
	35	10592	11649	-9.1	1390	1416	-1.8
2	15	3874	3959	-2.1	1255	1191	5.4
	20	5714	5796	-1.4	1333	1247	6.9
	25	7681	7875	-2.5	1400	1269	10.3
	30	9873	10035	-1.6	1439	1473	-2.3
	35	12523	12163	3.0	1504	1479	1.6
3	15	4214	3947	6.8	1233	1172	5.2
	20	6085	5715	6.5	1397	1234	13.3
	25	8578	7762	10.5	1417	1248	13.6
	30	10305	9845	4.7	1491	1447	3.1
	35	12635	11974	5.5	1505	1453	3.5
4	15	2162	2420	-10.7	652	707	-7.8
	20	3598	3567	0.9	758	738	2.8
	25	5194	4871	6.6	824	755	9.1
	30	6311	6177	2.2	883	917	-3.7
	35	8330	7511	10.9	926	923	0.3
Max				10.9			13.6
Min				0.9			0.3

The relative differences between the results from the two approaches are also given in the tables. As can be seen, the absolute differences observed are between 0.9% and 10.9% for the mid-span moment and between 0.3% and 13.6% for end shear. This indicates that the simplified model gives reasonably good estimates of the characteristic values in all cases. It is clearly possible to get a low value of $\alpha_M L$ and $\alpha_S L$ for a particular site. However, it is highly significant to find values which are consistent across from different sites with completely different traffic and a wide range of spans. It should also be mentioned that when $\alpha_M L = 0.63$, not all axles are on the bridge for spans of 25 meters and less. For $\alpha_S L = 0.42$, all axles of the lighter truck are involved in the critical loading cases for all spans with the exception of the 15 metre span bridge where only the last four axles are involved.

7. Conclusions

This work presents a site-specific simplified traffic load model that generates characteristic load effects which can otherwise only be determined utilising a complex simulation technique. The results show that it is mostly 5-axle trucks, considering their weights and lengths, which are involved in the critical loading scenarios. For data at each of four sites pairs of heavy trucks with weights derived from the measured data are placed at specified locations on the bridge. The same locations of the trucks are valid for all sites considered. The simplified model gives reasonably comparable characteristic load effects to those obtained from full simulation. The authors believe that the results can be employed by practicing engineers for bridge assessment without having to perform full simulations.

Acknowledgements
The authors gratefully acknowledge the cooperation of the Laboratoire Central des Ponts et Chaussées (LCPC), Paris and the Road and the Hydraulic Engineering Division (DWW) of the Dutch Ministry of Transport for supplying WIM data.

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ANALYSIS OF TRAFFIC LOAD EFFECTS ON RAILWAY BRIDGES USING WEIGH-IN-MOTION DATA

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Abstract

This paper concentrates on the statistical methods of evaluating traffic load effects on railway bridges and primarily considers the ultimate limit state. The study utilizes data from a weigh-in-motion site which records, for each train, the train speed, the static load from each axle and the axle-spacing. Only single track short to medium span bridges are considered in the paper as these are typical items chosen for code calibration purposes. The load effects are analyzed by two methods, the first is the classical extreme value theory where the load effect is modeled by the family of distributions called the generalized extreme value distribution (GEV). The other method adopts the peaks-over-threshold method (POT) where the limiting family of distributions for the heights to peaks-over-threshold is the Generalized Pareto Distribution (GPD). In this latter method the choice of the threshold level is discussed and the compliance to the GPD model is recognized from the behavior of the curve of the mean exceedance plots. In each case uncertainties surrounding the distribution parameter estimates are approximated using the asymptotic properties of the estimators and in this manner confidence levels surrounding for e.g. the obtained 50 year return loads can be estimated.

Keywords: Weigh-in-Motion, Peaks-over-Threshold, Extreme Value Theory, Traffic Loads Effects, Railway, Bridge, Generalized Pareto Distribution.

Résumé

Cet article se focalise sur les méthodes statistiques pour l'évaluation des sollicitations du trafic sur les ponts ferroviaires, et principalement sur les états limites ultimes. L'étude utilise des données de pesage en marche sur un site où ont été enregistrés pour chaque train, la vitesse, la charge de chaque essieu et les distances inter-essieux. On ne considère que les ponts de portée moyenne à une voie, car ils sont représentatifs de ceux utilisés pour l'étalonnage des codes. Les sollicitations sont analysées par deux méthodes. La première est la théorie classique des valeurs extrêmes, dans laquelle la sollicitation est modélisée par une famille de distributions appelée distribution de valeur extrême généralisée (GEV). La seconde utilise le principe des pics au-dessus d'un seuil (POT) dans lequel la famille de distribution des pics au-dessus d'un seuil se limite à une distribution de Pareto généralisée (GPD). Dans cette dernière méthode, le choix du seuil est discuté et l'adéquation de la du modèle GPD est déduite du comportement de la courbe des dépassements moyens. Dans chaque cas les incertitudes sur l'estimation des paramètres de la distribution sont approximées à l'aide des propriétés asymptotiques des estimateurs, de sorte que les niveaux de confiance des charges à période de retour donnée (par ex. 50 ans) puissent être estimés.

Mots-clés: Pesage en Marche, Pics au-dessus d'un Seuil, Théorie des Valeurs Extrêmes, Sollicitations du Trafic, Chemin de Fer, Pont, Distribution Généralisée de Pareto.

使用動態地磅資料分析鐵路橋梁之載重效應

摘要：

本篇文章著重於探討評估鐵路橋梁載重效應之統計方法並討論其極限情況。本研究利用動態地磅測站 (Weigh-In-Motion, WIM) 所收集之資料進行分析，該資料記錄每一輛列車之速度及每軸之靜態載重與軸距。本研究僅考慮單軌且短至中跨距之橋梁，因爲此種橋梁被選爲進行程式校估之標準資料。載重效應可採用兩種不同之方法進行分析；第一種爲標準極限值理論，該理論利用軸重分佈家族亦稱爲廣義極限分佈 (the generalized extreme value distribution, GEV) 進行載重效應分析：另一種則採用超過門檻值之尖峰值方法 (peaks-over-threshold, POT) 進行探討，該方法其分佈家族爲 Generalized Pareto Distribution(GPD)。 本文將針對第二種方法中門檻值之選取進行討論，並利用 mean exceedance plot 進行門檻值與 GPD 方法之適合度驗證。每一個案例中分佈參數之估計值利用其漸進的性質近似而得，在上述情形下可估計 50 年之回歸載重。

關鍵字：動態地磅、超過門檻值之尖峰值、極限值理論、載重效應、鐵路、橋梁、GPD

1. Introduction

Railway infrastructure owners are faced with the problem of an aging bridge stock. In Sweden many of the railway bridges date back to the early 1900 (Paulson et. al. 1998) and are already carrying loads in excess of those originally intended during design. The increased demands on the railway infrastructure means that there is a constant need to improve the methods for assessing existing bridges, both for extending their service life and also for upgrading bridges for increased allowable axle loads, line loads and train speeds. Traditionally much of the research surrounding the assessment procedures has concentrated on material strengths and relatively little is done to assess the actual traffic loads on railway bridges. Analysis of WIM data provides a tool with which the knowledge of the actual traffic loads and their effects may be increased and may lead to the more efficient utilization of the existing bridge stock.

As an engineer, one is often interested in establishing the maximum loading on a structure in a given reference period of time. We are often required to estimate the characteristic load on a structure, e.g. the 50-year return load, from WIM data recorded from a much shorter period., One is, therefore, forced to extrapolate long past the available data in order to make predictions about events with a very low risk of occurrence. This extrapolation from a mathematical point of view is not strictly justifiable (Caers and Maes, 1998). In the preface to (Coles, 2001) the validity of extrapolation is discussed at length and admits that it is easy to criticize extrapolation of this kind. However, it is also noted that extrapolation is demanded and that the extreme value theory provides the only real mathematical model with which to do this.

Extreme value theory has been used in many disciplines of civil engineering to describe the loading distributions of variable loads and even the strength of materials. Extreme value theory has been used in oceanography to describe maximum sea levels (de Haan, 1993), in wind engineering, in mining to estimate the occurrence of large diamond and precious stone deposits (Caers et al., 1998) and to predict extreme traffic load effects on road bridges (Cremona, 2001; O'Connor et al., 1998). It has even been used in financial applications to describe and predict high insurance claims and in stock market applications (Embrechts et al., 1997; Emmer et al., 1998; Rootzén and Tajvidi, 1997).

There are two basic approaches to extreme value theory; the classical approach which involves dividing the data into subsets of data and thereafter selecting the maxima. These maximum values are then often fitted to an Extreme Value Distribution for maxima. The Extreme Value Distributions may be expressed in the form of the Generalized Extreme Value Distribution (GEV). This approach is illustrated in the upper two figures of Figure 1. An alternative method is to use the peaks-over-threshold (POT) approach. In this case, a high threshold level is chosen and the distribution of the heights to the peaks above the threshold is fitted to a Generalized Pareto Distribution. The advantage of the latter method is that all the interesting points above the threshold may be used in the parameter estimation of the extreme behavior whereas in the traditional method a single subset may contain several high interesting values but only the largest in each subset is used in the parameter estimation. This POT approach is illustrated in the lower two figures of Figure 1.

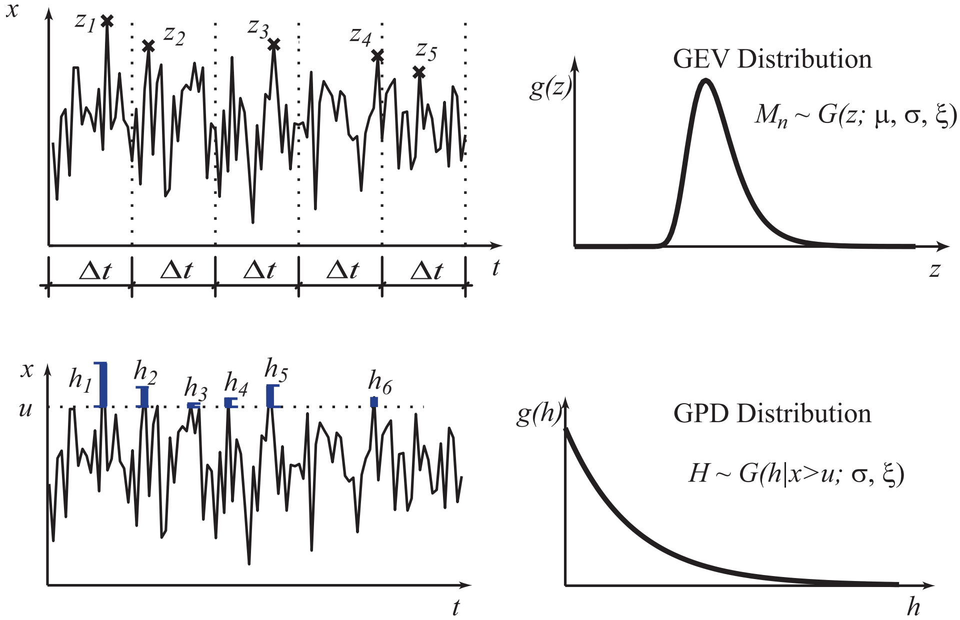


Figure 1 –The Upper Two Diagrams Illustrate the Principal of the Classical Approach to Extreme Value Theory while the Lower Diagrams Illustrate the Peaks-over-Threshold Method

There are several text books on the subject of extreme value theory and their applications. One of the pioneering works can be found in (Gumbel, 1958), while from an engineering applications point of view the book (Castillo, 1987) is very useful in explaining the fundamentals, while the books (Embrechts et al., 1997; Leadbetter et al., 1997) provide a mathematically more rigorous account of the subject together with the underlying assumptions. The book (Coles, 2001) provides the background to the distributions and also shows several examples of the use of the distributions and how they can be used for inference purposes.

1.2 Generalized Extreme Value Distribution

The *classical* approach to extreme value analysis is briefly described below, however, for a full description of the theory the reader is referred to one of the above mentioned books. The approach considers the distribution of M_n such that

$$M_n = \max(X_1, X_2, \ldots, X_n) \tag{1}$$

where $X_1, X_2, \ldots, X_n$ are independent identically distributed (i.i.d.) random variables that come from the distribution function F. The random variables are often related to a time period e.g. the maximum daily sea level or the maximum daily wind speed, in this example with n equal to 365, M_n. will refer to the maximum yearly distribution. The distribution of M_n may be calculated from the original distribution F by

$$\begin{aligned} \Pr(M_n \le z) &= \Pr(X_1 \le z), \Pr(X_2 \le z) \ldots \Pr(X_n \le z) \\ \Pr(M_n \le z) &= [F(z)]^n \end{aligned} \tag{2}$$

where Pr denotes the probability of an event.

Equation (2) is a popular method for analyzing WIM data especially for live load effects from road traffic. The original distribution F is often assumed to be normally distributed and an estimation of the original distribution is obtained by fitting the observed WIM data x to a normal distribution. However, the disadvantage of this method is that, according to (Coles, 2001), small discrepancies in the estimation of F can lead to large errors for the distribution of M_n.

As n increases $M_n \rightarrow \infty$. Therefore, a normalization is required such that; $M_n^* = (M_n - b_n)/a_n$.

$$\Pr\left[(M_n - b_n)/a_n \leq z\right] \rightarrow G(z) \quad \text{as} \quad n \rightarrow \infty \tag{3}$$

Provided G is non-degenerate then $G(z)$ denotes one of the extreme value distribution functions cf. (Embrechts et al., 1997; Castillo, 1987; Coles, 2001). These three families of distributions can be collectively expressed in the *Von Misses* form known as the Generalized Extreme Value distribution. The cdf of the GEV is given by

$$\begin{aligned} G(z;\xi,\sigma,\mu) &= \exp\left\{-\left[1+\frac{\xi(z-\mu)}{\sigma}\right]^{-1/\xi}\right\} \quad \text{if} \quad \xi \neq 0 \\ G(z;\xi,\sigma,\mu) &= \exp\left\{-\exp\left[-\frac{(z-\mu)}{\sigma}\right]\right\} \quad \text{if} \quad \xi = 0 \end{aligned} \tag{4}$$

where σ, μ and ξ are the scale, location and shape parameters respectively. The formula is valid for values of z that fulfill the condition $[1 + \xi(z-\mu)/\sigma] > 0$ and where $\sigma > 0$ and ξ and μ are arbitrary. The case of $\xi = 0$, $\xi > 0$ and $\xi < 0$ correspond to the Gumbel, Fréchet and the Weibull distributions respectively. The shape parameter ξ is also known as the extreme value index (EVI). The value of the shape parameter is vital in determining the tail behavior of the distribution (Caers and Maes, 1998). When $\xi < 0$ the distribution has a finite upper limit given by $\mu-\sigma/\xi$. When $\xi > 0$ the distribution has a heavy tail i.e. a slow approach towards infinity.

1.2 Generalized Pareto Distribution

The Peaks-Over-Threshold method is an alternative method to the classical approach described. The theory of this method is that regardless of the behavior of the main part of the distribution, the tail of a distribution above a high enough threshold, u, can be shown to tend to a Generalized Pareto Distribution. The theory behind the POT method is not discussed here and can be found in (Leadbetter et al., 1997; Brodtkorb et al., 2000; Rydén and Rychlik, 2001; Coles, 2001; Naess and Clausen, 2001; Embrechts et al., 1997).

As in the case of the classical approach one considers a set of i.i.d. random variables, $X_1, X_2, \ldots,$ X_n, that come from the distribution function F. Then provided the threshold level u is large enough the distribution of the excursion heights, $h = (X-u)$ under the condition that $X > u$, is approximately given by

$$G(h;\xi,\sigma)=\begin{cases}1-\left(1+\dfrac{\xi h}{\sigma}\right)^{-1/\xi} & \text{if} \quad \xi\neq 0\\ 1-\exp\left(-\dfrac{h}{\sigma}\right) & \text{if} \quad \xi=0\end{cases} \tag{5}$$

for $0 < h < \infty$ if $\xi \geq 0$ and for $0 < h < -\sigma/\xi$ if $\xi < 0$. Where σ is a positive scale parameter, ξ is the shape parameter and h is the height of the peak above the threshold value. As with the GEV the shape parameter of the GPD is dominating in determining the behavior of the tail. If $\xi \geq 0$ the tail is unbounded while on the contrary if $\xi < 0$ the tail has an upper bound at $u-\sigma/\xi$.

1.3 Return Loads

The return load or return level, is defined as the load that has a probability p of being exceeded in the time period relating to the distribution, i.e. under certain statistical conditions, on average the load will occur with a period of $1/p$. If the distribution $G(z)$ is the distribution of the yearly maxima, then the load with a probability p of being exceeded, will on average be exceeded once ever $1/p$-years. The return load can be found by inverting (4) which can be shown to yield the result:

$$z_P=\begin{cases}\mu-\dfrac{\sigma}{\xi}\left\{1-\left[-\log(1-p)\right]^{-\xi}\right\} & \text{if} \quad \xi\neq 0\\ \mu-\sigma\log\left[-\log(1-p)\right] & \text{if} \quad \xi=0\end{cases} \tag{6}$$

such that $G(z_p) = 1-p$.

The return loads for the POT method is a little more complicated as the time concept must be incorporated into the expression, a full account of the derivation can be found in (Coles, 2001). Under the assumption that the GPD model is applicable and that the parameters of the GPD are ξ and σ, then the N-year return load Z_N will be given by

$$Z_N=\begin{cases}u+\dfrac{\sigma}{\xi}\left[\left(N\,n_y\rho_u\right)^{\xi}-1\right] & \text{for} \quad \xi\neq 0\\ u+\sigma\log\left(N\,n_y\rho_u\right) & \text{for} \quad \xi=0\end{cases} \tag{7}$$

where ρ_u is the probability that an observation will exceed the threshold limit u, and n_y is the number of observations equivalent to one year of sampling. The Maximum Likelihood estimator of ρ_u is given by

$$\hat{\rho}_u=\frac{k}{n} \tag{8}$$

where k is the number of observations that exceed the threshold and n is the number of observations. According to (Coles, 2001) the number of exceedances of u is binomially distributed Bin(n, ρ_u).

1.4 Parameter Estimates

There are various methods to estimate the parameters of the generalized extreme value distribution and the three extreme value distributions. Methods for calculating the shape parameter can be found in e.g. (Beirlant et al., 1996b; Smith, 1987; Dekkers and de Haan, 1989; Dekkers et al., 1989; Grimshaw, 1993). In the work presented here the *Matlab* toolbox, from the Department of Mathematics at Lund University called *WAFO*, was used. The toolbox together with an accompanying manual (Brodtkorb et al., 2000) are free on the internet; however, the toolbox requires *Matlab* in order to run. Several different methods are available within the WAFO function, called *wgevfit,* for estimating the parameters of the GEV. Within the same toolbox parameter estimates for the GPD can be made using a function called *wgpdfit.*

1.5 Estimating Uncertainties and Confidence Levels

The value of the return loads obtained from either equation (6) or (7) will contain uncertainties associated respectively with the estimation of the parameters of the GEV or the GPD. Besides providing the parameter estimates, both the *WAFO* functions *wgevfit* and *wgpdfit* also yield an asymptotic variance-covariance matrix of the estimates, $V(\hat{\xi},\hat{\sigma},\hat{\mu})$ and $V(\hat{\xi},\hat{\sigma})$ respectively. It can be shown, according to (Brodtkorb et al., 2000; Coles, 2001), that the estimates are, at least asymptotically, the unbiased estimates and that the distribution of the estimates are multivariate normal with the above mentioned variance-covariance matrix. This fact can, therefore, be used when building confidence intervals, either of the parameter estimates or of the return or characteristic load.

Random values of $\hat{\xi}$, $\hat{\sigma}$ and $\hat{\mu}$ can therefore be simulated whose values retain the dependencies given by the variance-covariance matrix. According to (Englund, 2000) the Choleski method can be used whereby a matrix $\boldsymbol{A}$ is found such that $\boldsymbol{V}=\boldsymbol{A}\boldsymbol{A}^{\mathrm{T}}$. A d-dimensional independently standard normally distributed variables N(0,1) $Z_1, Z_2, Z_3, \ldots Z_d$ can then be produced. A column vector, $\boldsymbol{Z} = (Z_1, Z_2, Z_3, \ldots Z_d)^{\mathrm{T}}$ can then be used such that

$$\mathbf{X} = \mathbf{m} + \mathbf{AZ} \tag{9}$$

where $\boldsymbol{m}$ are the mean values; in the GEV case d is three dimensional and $\mathbf{m} = \begin{pmatrix}\hat{\xi} & \hat{\sigma} & \hat{\mu}\end{pmatrix}^T$. The matrix $\boldsymbol{A}$ can easily be found with the help of the *Matlab* function *sqrtm*. These randomly produced parameters of the GEV or the GPD distributions are then used in (6) or (7), respectively, to produce the estimated distribution of required return load. The simulated values of the return load can be structured into ascending order having index from say 1 to n, and the 95% quantile value is estimated using the $0.95n$-th value in this ordered sample. Typically one thousand simulations were used to estimate the distribution of the 50 year return load.

As regards the estimations from the POT model the variance-covariance matrix should also include the uncertainties involved in the estimate of ρ_u, however according to (Coles, 2001) these are usually small in comparison with the variances of the estimators of the GPD parameters.

The Mean Exceedence Plot, also known as the Mean Residual Life Plot can be used to determine at what threshold level the exceedance heights start to behave as predicted by the GPD model. If the data complies with the GPD model then a plot of the mean value of h for increasing values of u should show a linear behavior provided $\xi < 1$ (Brodtkorb et al., 2000; Coles, 2001). If the condition that $\xi < 1$ is not fulfilled then a Generalized Pareto Quantile Plot needs to be used to indicate compliance with the GPD model, see (Caers and Maes, 1998; Beirlant et al., 1996a; Beirlant et al., 1996b) for further details.

So-called Quantile-Quantile plots, abbreviated QQ-plot cf. (Embrechts et al., 1997; Emmer et al., 1998, Coles, 2001), were used to visually check if two samples came from the same distribution. Other tests were carried out on the samples to check their compliance with the extreme value models, such as the Kolmogorov-Smirnov test, the Anderson-Darling test and measurements of the Mean Square Error, see (James, 2003).

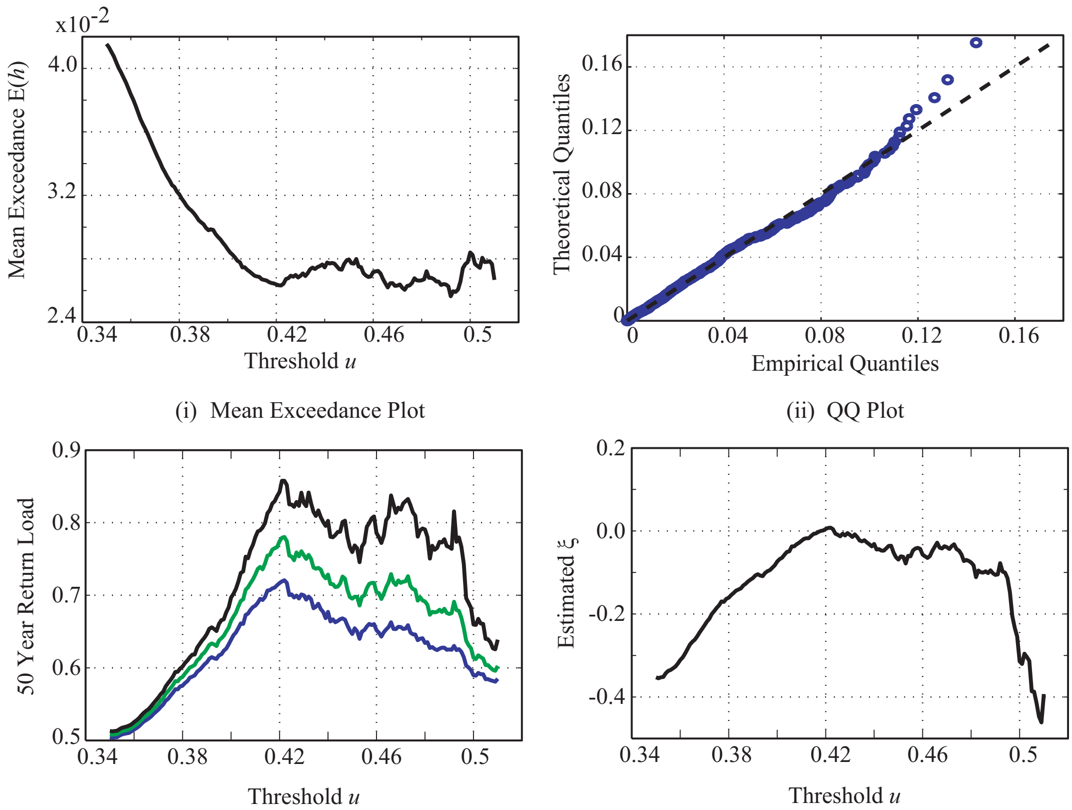
2. Application to WIM Data

The methods described above were used to analyze results from simulations using WIM data. WIM data containing information regarding individual axle weights, axle spacing and train speeds were used to simulate traffic load effects on short to medium span simply supported bridges. Six spans were considered in the range 4 to 30 meters. The load effect considered was the mid-span moment. The dynamic effects of the moving trains were accounted for by simulation, using a computer program written at this department for *Matlab*, see (Karoumi, 1998). In the computer program the bridges were represented by simple two dimensional FEM beam elements while the different axles were modeled using the so-called moving force model. In the computer program mode superposition is used to calculate the response of the structure. The moving force model can not take into account the effects of track irregularities and this was therefore accounted for afterwards, using formula described in the Eurocode, cf. (CEN, 1995).

Approximately four months of continuous WIM traffic data was used in the analysis which was taken from a site deemed to be representative for Swedish rail traffic conditions, containing a variety of traffic types such as passenger, mixed freight and block trains. This traffic data consisted of more than 7400 trains and the long lengths of the trains required extensive computer processing time. All simulated moments were normalized by the moment at mid-span derived from the characteristic traffic load LM71 or SW/2 of the Eurocodes (CEN, 1995) and included the dynamic factor but excluded the partial safety factor. For a more thorough description of the simulations see (James, 2003). In the GEV approach the trains were subdivided into sets of 50 from which the maximum simulated moment was used when estimating the parameters of the GEV model.

3. Results

Figure 2(i) shows an example of a mean exceedance plot. The linearity of the curve after approximately $u = 0.42$ indicates compliance with the GPD model. This is also indicated by the relative stability of the estimate for the scale parameter ξ which can be seen in Figure 2(iii) and (iv) and remains at value just below zero for $0.42 \leq u \leq 0.49$. After the value of $u = 0.49$ the number of points remaining on which to make a satisfactory estimate becomes small and large variations in the estimated parameters are observed. A discussion of the problem of choosing a threshold value that is long enough into the tail so as not to create bias but at the same time provide a suitable number of points on which to make a reliable parameter estimate can be found in (Caers and Maes, 1998). The finally chosen value for the threshold in this case was 0.458 and a QQ plot of the theoretical versus the empirical quantiles for the eceedances over this threshold can be seen in Figure 2(ii). It is possible to see from this diagram that the fitted GPD model provides a good approximation of the data and in this case is conservative as the theoretical quantiles predict higher values than those actually observed.



(i) Mean Exceedance Plot

(ii) QQ Plot

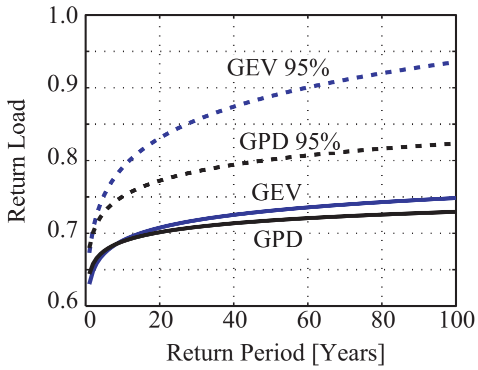
(iii) 95 % Upper and Lower Confidence Levels of the 50 year Return Load

(iv) Shape Parameter vs. Threshold Plot

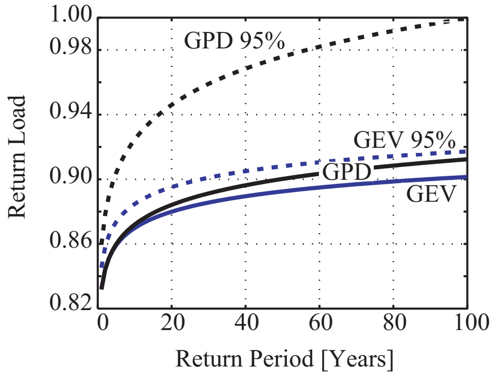
Figure 2 - Examples of Various Plots Relevant to the GPD Model for a 20 m Span Bridge

Figure 2(i) shows a linear behavior after $u \approx 0.42$ indicating compliance with the GPD model. This stability of the results can also be seen in Figures (iii) and (iv) for $0.42 \leq u \leq 0.49$. The chosen threshold in this case was 0.458 and the QQ plot for this value is shown in Figure (ii).

Figure 3 shows a typical comparison of the results obtained from the GEV and the GPD approach. In general, and as can be seen from the figure, both methods provided similar results for the mean value of the estimated return loads. However, the variances associated with the estimates as shown by the 95 % upper confidence level varied for the two methods and for the considered span. No one method yielded constantly lower estimation variances. The mean values in most cases gave very comparable results while the variances surrounding the estimates could be higher in either model depending on the studied span.



(i) Span of 20 Meters



(ii) Span of 8 Meters

Figure 3 - Comparison of the Return Loads Derived Using the GEV and the GPD Model

4. Conclusions and Discussions

In general both the GEV and the GPD models provided suitable models for the studied load effect. The load effects from the shorter span bridges, 10 m or less, were more difficult to fit to the models. This was believed to be due to the dominating effect of highly loaded individual axles or bogies on these short span bridges as the measured data included a few very high possibly erroneous values. The measured axle loads indicated cases of extremely high overloading often in excess of 30 tonnes on a 22.5 tonnes rated line. In the analysis all values are included although it can be discussed whether these values are real overloads or measuring errors. The estimated return loads or reliability indices were very sensitive to estimated values of the shape parameter ξ. Values of $\xi \geq 0$ yielded unbounded return loads while on the contrary if $\xi < 0$ the tail of the distribution has an upper limit. A rail freight car suspension obviously has an upper limit depending on spring stiffness and the restricted loading area in a freight car. However, this physical upper limit may be so high as to be irrelevant for practical applications.

In the GEV model only the subset of 50 trains was analyzed when taking the maximum. This was chosen as it approximately represented one day of traffic. On hind sight it may have been better to subdivide into precisely one day periods as rail traffic mostly follows daily traffic schedules. The effect of changing the number of trains included in each subset has not been considered when adopting the GEV method. It would be interesting to study this effect as it is analogous with that of changing the threshold level in the POT method.

Despite this relatively long measuring period of four months, the methods still require extensive extrapolation past the available data and therefore necessarily involve a high degree of uncertainty. These methods are based on sound mathematical models and provide a means of evaluating the uncertainties involved.

The study has only considered the ultimate limit state, however, the use of the POT method should be valuable for accessing the likelihood that a certain stress level has or will be exceeded. It can therefore be used in fatigue analysis and is perhaps especially relevant when determining the likelihood that concrete has cracked or not.

Acknowledgements
The author gratefully acknowledges the Swedish National Rail Administration (Banverket) for their financial support to this research project.

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SLOVENIAN EXPERIENCE OF USING WIM DATA FOR ROAD PLANNING AND AINTENANCE



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Abstract

Over the last 3 years a network of 30 WIM sites has been established in Slovenia to cover all major routes of the main state road network with portable bridge WIM system. Results of measurements revealed that everywhere the real traffic loading was higher than if calculated according to the Technical specifications for traffic loading. Furthermore, overloading turned to be a serious problem and thus WIM system were used also to select locations and periods for static weighing control with the police. Consequently, a high-speed WIM enforcement procedure is being discussed. A study based on measured WIM data showed that when applying appropriate tolerances of WIM system the sum of overloading fines could exceed 300 million Euros per year which is approximately 30 times more than it is collected at present from static weight controls. Unfortunately, the present legislature in Slovenia does not allow yet using weigh-in-motion data for direct enforcement of the overloaded vehicles.

Keywords: SiWIM, Bridge WIM System, Enforcement, Mobility, Overloading, Loading, Traffic.

Résumé

Au cours des 3 dernières années un réseau de 30 WIM sites a été établi en Slovénie pour couvrir toutes les routes principales d'état avec les systèmes portatifs de pesage par pont instrumenté. Les résultats des mesures ont indiqué que partout le vrai chargement de trafic était plus haut que si s'accorder calculé selon les spécifications techniques pour le chargement de trafic. En outre, la surcharge tournée pour être un problème sérieux et système de WIM ont été employées ainsi également pour choisir des endroits et des périodes pour la commande pesante statique avec la police. En conséquence, une procédure d'application des surcharges automatique avec WIM est discutée. Une étude basée sur des données mesurées de WIM a prouvé qu'en appliquant des tolérances appropriées de système de WIM que la somme des fines de surcharger pourrait excéder 300 millions d'Euros par an ce qui est approximativement 30 fois davantage qu'il est rassemblé actuellement des commandes statiques de poids. Malheureusement, la législature en Slovénie ne laisse pas employer encore des données de pesage en marche pour l'application directe des véhicules surchargés.

Mots-clés: SiWIM, Pesage par pont Instrumenté, Application, Mobilité, Surchargeant le Chargement, le Trafic

斯洛維尼亞使用動態地磅資料進行道路規劃及維護之經驗

摘要：

過去三年來斯洛維尼亞以移動式橋梁動態地磅建立了主要州(省)道路網上主幹道之 30 個動態地磅網路(Weigh-in-Motion, WIM)。 量測資料顯示真實之車輛載重皆較利用技術規範計算而得之載重爲高。再者，因爲超載已演變成爲一個嚴重的問題，因此動態地磅系統可作爲選擇靜態地磅站需配合警力執法之時間與位置之依據。因此，本文中亦針對高速動態地磅執法程序進行探討。研究顯示當應用適當之動態地磅放寬系統時，超載罰款之總額每年可超過 3 億歐元，並幾乎爲利用現有靜態地磅站執法所收取費用之 30 倍。但不幸的是，斯洛維尼亞現有法令仍不允許利用動態地磅資料進行超載之直接取締。

關鍵字：橋梁動態地磅系統、執法、機動性、超載、載重、交通

1. Introduction

With its 20.000 km² Slovenia is one of the smallest countries of the European Union. It however plays an important role from the transport point of view as it is crossed by two of the heavily trafficked Trans European corridors: the 5th, going from South West to the North East of Europe (Barcelona – Kiev), and the 10th, going from the North West of Europe to Turkey and Greece.

Slovenia's 7000 km long state road network is equipped with around 600 mainly automatic traffic counters that provide up-to-date information about the traffic volumes. Traditionally, this data has also been the main input for the ESAL (Equivalent Single Axle Load) method, which is used in design and maintenance of pavements. As counting data cannot give any information about real axle loads, especially about their overloading, the Slovene Road Administration decided to start acquiring the weigh-in-motion (WIM) data. Over the last 3 years a network of 30 WIM sites has been established to cover all major routes of the main state road network (Figure 1). Four portable bridge WIM systems are used to perform the 7-day measurements twice per year on each of the sites. The results of weighing exceeded some of the most pessimistic expectations.

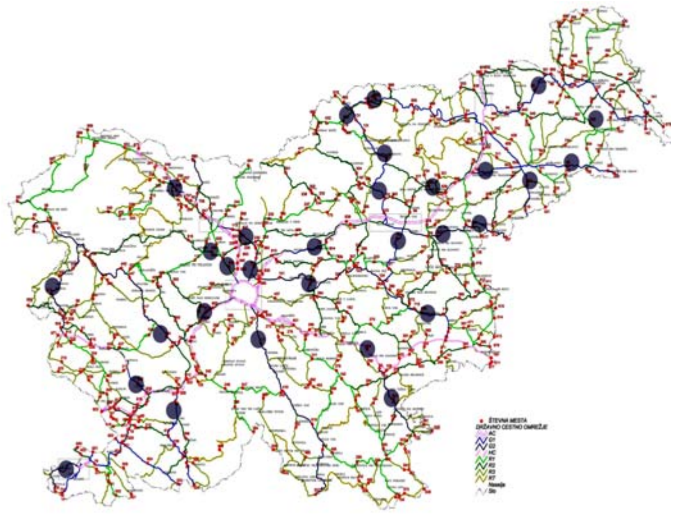


Figure 1 – Slovenian Network of WIM Sites

2. WIM (Weigh-In-Motion) Measurements

Traffic counters collect traffic volume data and are therefore essential when collecting data for traffic, freight and other analyses. They however do not provide any information about the real axle loads, which is an important parameter when assessing realistic pavement or bridge loadings. Axle loads can only be obtained with WIM measurements, where all free flow vehicles heavier than 3,5 t are weighed. This data is typically used to calculate load effects on pavement, most often using the ESAL (Equivalent Single Axle Load) methods.

There are 2 major groups of WIM systems available on the market, the better known pavement and the relatively new bridge WIM systems. The main difference between them is that while all pavement WIM systems require sensors that are built into the top layer of the pavement, the bridge WIM systems, such as the Slovenian SiWIM, instrument the existing bridges with sensors and thus, the superstructures of these bridges act as the measuring platforms. Deflections (strains) of the structures are then, with information about the speed and axle distances of vehicles, used to calculate the axle loads and the gross weight.

The main advantages of the SiWIM system are:

- high accuracy of results due to the long weighing platform,
- system can be installed without damaging the pavement,
- they cause minimal or even no disturbance of the traffic and thus no traffic delays,
- system can be easily and price-efficiently moved from one location to another without influencing accuracy of the results.

3. WIM Results – the Slovene Example

Based on some preliminary test measurements in years 2000 and 2001, the Slovene Road Administration decided in 2002 to start collecting traffic data at 20 different locations on the main road network. A year after this number was extended to 30 sites. Each location is visited twice a year and every time the measurements last for 7 days. Four SiWIM systems are used to accomplish the 60 measurements in around 8 months. From each location 14 days of information of vehicles heavier than 3,5 tonnes is collected: axle loads, gross weight, axle distances, speed, class (type of the vehicle), time and date of passage, temperature etc..

4. Calculation of Traffic Loading

Accurate traffic loading data is essential for efficient planning and reconstruction of roads. The Slovenian specifications for traffic loading (TSC 2001), from hereon denoted as *Specifications*, account for the traditional ESAL (Equivalent Single Axle Load) method. One ESAL is defined as a 4-wheel single axle of 82 kN and all other axles are compared to such nominal axle. Then, the total load effect of a traffic flow is calculated using the formula:

$$ESAL = 10^{-8} \times \sum_{i=1}^{N} f_o \times (f_k \times A_i)^4 \tag{1}$$

where:

ESAL - influence factor of axle load according to nominal axle load of 82 kN
f_o - axle type factor (2,212 for single, 0,0195 for double and 0,0048 for triple axles)
f_k - wheel type factor (1,0 for twin regular, 1,2 for super single (wide) and 1,3 for regular single tires)
A_i - individual axle loads in kN
N - number of axles

The well known effect of this formula is that, due to the power of 4, the traffic loading is not proportional to the axle load. For example, a 20% raise of axle load increases the ESAL value for 107%.

5. Weigh-In-Motion Results

A whole range of different results was obtained from the measured WIM data to get an overview about the traffic loading situation on the Slovene main roads. At present data is mainly used for traffic planning, but also for pavement design and reconstruction and in limited cases, for bridge assessment and for calculation of load limits on bridges.

Clearly, contribution of different categories of vehicles was different (Figure 3). The articulated vehicles (tractor-trailers and semi-trailers), for example, contribute almost 60% to the total loading, while all cars and light vehicles with gross weight below 3,5t can be neglected, with less than 0,1% of total contribution. Then, loading varied considerably from one site to another. Figure 4, above, exhibits ratio of 1:20 between the most and the least trafficked road sections. Also, results prove that the number of overloaded vehicles does not say much about the real overloading. On one side the lowest overloading (5% of additional ESAL values) was caused by 9% lightly overloaded vehicles (site 19 in Figure 4, below). The other extreme was the site 10 with 103% of additional ESAL values caused by 25% of the overloaded vehicles.

Figure 2 – Two Examples of Bridges Used for Regular WIM Measurements in Slovenia

Not unexpectedly, the real loading and loading calculated by multiplying the traffic counting data with the general factors from the Specifications (the 100% line) differ considerably. While on the least trafficked section the measured value was only 5% higher than if obtained from the Specifications, an increase of +188% was observed on a site with high number of heavily overloaded vehicles. In other words, in this case the pavement carried 188% more loading than it can be calculated from the Specifications. Green bars show values with supposition of no overloading on these sections, i.e. in a case that all overloaded vehicles would be loaded only to their legal limits. Even in such unrealistic case the Specifications would overestimate the traffic in only 2 cases, which clearly indicates that the present loading factors in the specifications need to be thoroughly revised.

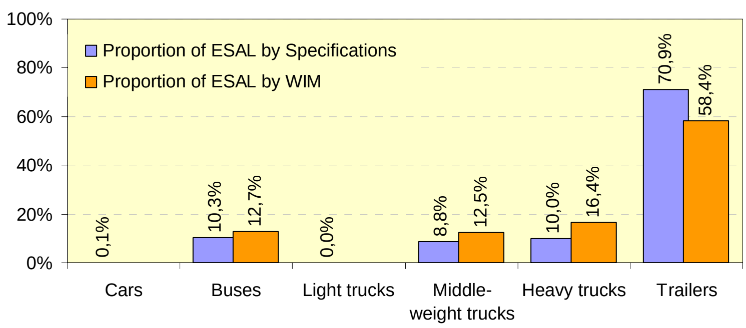
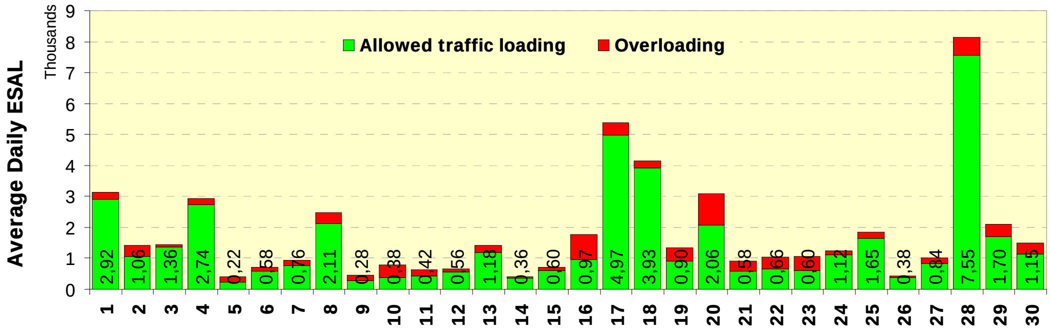
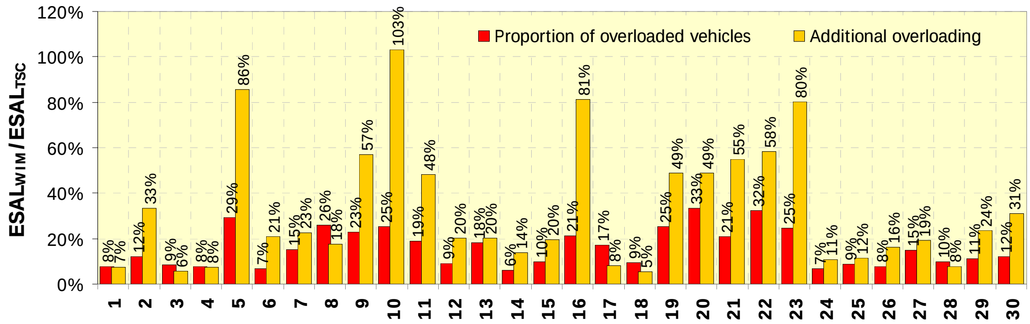


Figure 3 – Proportion of Cumulative ESAL Values per Vehicle Category



(a)



(b)

Figure 4 – (a) Proportion of Cumulative ESAL Values per Vehicle Category; (b) Additional Loading Compared to the Specifications with Proportion of Overloading

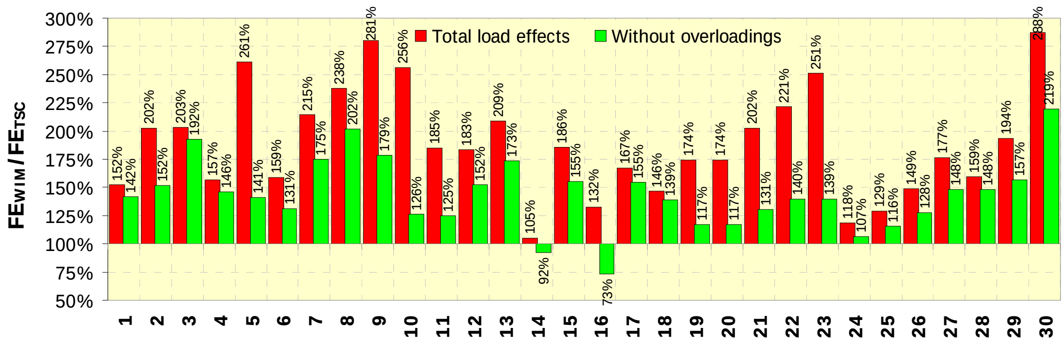


Figure 5 – Increase of the Real Traffic Loading Compared to the Values from the Specifications

6. Accuracy of Results

Accuracy was for all 30 locations (60 measurements) calculated according to the COST 323 specifications (COST 323, 2002). In all cases 1 or 2 pre-weighed trucks were used for calibration and their runs were evaluated accordingly to obtain the accuracy classes. It must me noted however, that due to the nature of data collection and limited funding only simple calibrations were done. The advanced SiWIM features, for example the calibration by axle rank, were therefore not used. Nevertheless, if approach to the bridge was smooth, even classes A(5) for gross weight, for single axle and for multiple axle loads were not exceptional. The majority of measurements fell into accuracy classes B(10) and C(15). Bridges with bumpy approach caused accuracy to decrease to classes D+(20), D(25) and in one case even to E(30).

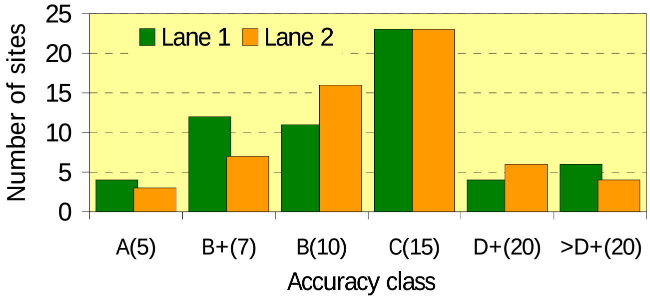


Figure 6 – Histogram of the Attained Accuracy Classes for 60 Measurements in Year 2003

7. Distribution of Traffic Loading and Overloading Along a Day

In order to specify the optimal time for the static weigh control, a further few WIM measurements were done for the Road Administration. Figure 7 shows traffic situation not far from a border crossing along a Sunday when in Slovenia the heavy vehicles over 7,5 tones gross mass are not allowed to drive between 6 o'clock in the morning and 10 o'clock in the evening. But then all of them, including some heavily overloaded ones, hit the road.

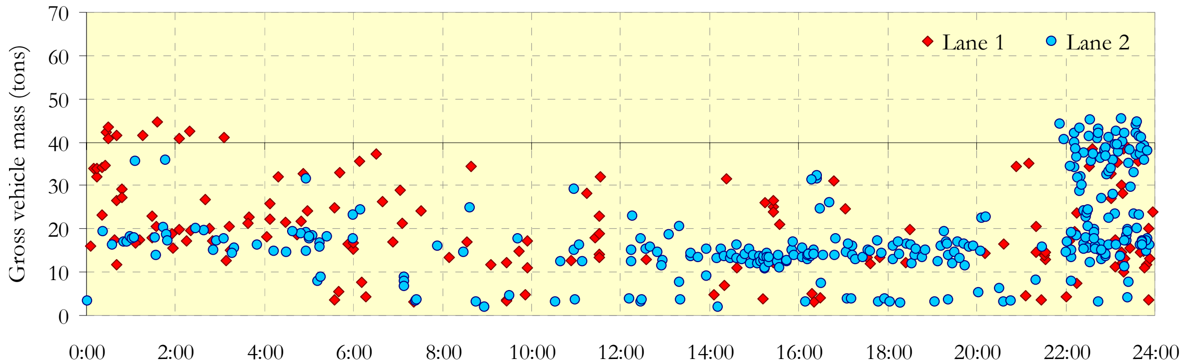


Figure 7 – Daily Distribution of Heavy Traffic

Figure 8 presents results of another WIM measurement which was done on a road from a motorway construction site to a land deposit site. The road section was critical because, first, with the axle load limit of 6 tones it was not intended for such heavy traffic and second, due to the construction site, heavy overloadings were expected. Results, however, were beyond any expectations. The total loading, expressed in ESAL values, was *8× higher* than if calculated according to the Specifications. Furthermore, due to the severe axle load limits, only 5% of the total 1745 ESALs were due to the legal loading and all the rest was overloading. On an average day, more than 70% of trucks over 3,5 tones in one of the 2 lanes were overloaded. The truck drivers were clearly aware of this as on the day when the static weighing control with the police was present, the total daily ESAL value fell to only 1/3 of the loading of other comparable days. Not surprisingly, the road was ruined long before the construction site was closed.

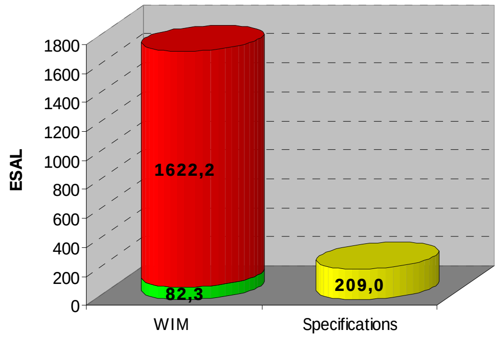


Figure 8 – Extension of Overloading on One of the Heavily Trafficked Sites

8. Potential for Enforcement

The three enforcement teams with static scales that circulate around Slovenia every day fined several thousands of overloaded trucks in 2003. This, however, corresponded to only 0,5% of all overloaded vehicles recorded with the WIM systems. Consequently, a high-speed WIM enforcement procedure is being discussed. It has been envisaged to account for the real accuracy of the WIM measurements and to specify the corresponding tolerances that would ensure 99,9% confidence in the results of the overloading vehicles. Applying such tolerances to the 2003 WIM data reduced the number of 'surely' overloaded vehicles to only 45% of the original number. But even if all of them were fined with amounts 10-times smaller than today, the sum of these fines would exceed 300 million Euros per year, which is 30 times more than it is collected with the present static controls. Unfortunately, the legislature in Slovenia does not allow yet using weigh-in-motion data for direct enforcement of the overloaded vehicles.

9. Conclusions

After many years of attempts WIM measurements have become a constituent part of traffic data collection for the Slovene road administration. Thirty sites were selected for regular measurements and are visited twice a year for a week.

Results showed that everywhere the real traffic loading was higher than if calculated according to the Technical specifications for traffic loading on roads, which in Slovenia are still used on a daily basis. This method simply multiplies the counting data by different factors that correspond to the type of the vehicles (light trucks, medium-sized trucks, heavy trucks, tractor-trailers and buses). WIM measurements proved that these factors are obsolete (they were adopted more than 20 years ago) and that they do not represent adequately the modern vehicle fleet. The real loading on all 30 sites exceeded the one from the Specifications on average for 80% and even for 188% in the worst case. The second reason for underestimation of true loading was that overloading is not accounted for at all in the present Specifications. Measurements revealed that on average every sixth heavy vehicle was overloaded, either its gross weight or at least one of the axles or both. This added 33% to the ESAL loading if compared to the regularly loaded vehicles, varying from 6% to 103% on different road sections. Furthermore:

- at some locations traffic loading was considerably different from one lane to another,
- results clearly identified the most critical types of vehicles on specific road sections and

- in some cases even a small number of overloaded vehicles considerably increased the total traffic loading on that road section.

Based on the success of the WIM measurements for collecting traffic data and for prescreening for static weight enforcement, new applications are being introduced. One of them is pre-selection for static weighing with camera and license plate recognition. The other one are measurements on bridges that need to be assessed. In this cases, the bridge WIM system can provide some additional statistically evaluated structural parameters, such as distribution of loads under traffic and dynamic amplification factors. The first set of 15 bridges is currently being worked on.

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SUMMARY OF SESSION 5 : APPLICATION OF WIM TO INFRASTRUCTURES (PAVEMENTS AND BRIDGES)

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Introduction

Session 5 focused on the application of WIM to infrastructures specifically pavements and bridges. Four papers were presented in this session focusing on traffic loads and pavement deformations, simplified site specific models for traffic loads, traffic load effects on railway bridges and using WIM for planning and maintenance.

Monitoring traffic loads and pavement deformations on a Swiss motorway

The paper by Raab et al presented by Poulikakos reported on the LTPP monitoring site on the A1 motorway between Zürich and Bern. The 250m long monitoring site has been recording data on the slow lane since 1998. WIM data using two rows of load cells with piezo-electric quartz sensors are combined with deformation data from sensors in the right wheel track and temperature sensors along different layers of the pavement.

The average daily distribution of heavy vehicles on workdays in 2000 and 2002 indicated the volume peaking at three distinct times 6-7, 10-11 and again 14-15. In 2001 the mode of data collection was changed from monitoring vehicles with GVW greater than 8t to vehicles with GVW greater than 3.5t. The aforementioned three peaks in traffic volumes remain with the new mode of data collection. What is apparent is that the difference between peaks is smaller.
This axel load data was used as a statistical fingerprint of the load history per day to enable a direct comparison between WIM data and deformation data as determined by the DDM deformation sensors. Relative vertical deformations of the pavement at various depths were measured using a system consisting of a number of Differential Deflection Measurement devices (DDM). These inductive measurement devices consist of a guide tube holding several LVDTs anchored at 1.5m with LVDTs fixed at different pavement depths.

A typical example of the surface plot comparing deformation at a depth of 12cm with the corresponding load in summer shows 3 peaks seen in both cases with the first peak dominant in load and deformation peaks having the same intensity. The latter is explained first by the fact that an increase in afternoon temperatures results in softening of the pavement and increase in deformation. Second, it is noted that the load diagram does not include the GVW>3.5t category. The fact that the deformation is not only caused by heavy vehicles (>8t) already led to a change in the recording of the WIM data, where since 2001 all vehicles >3.5t are monitored.

Furthermore, it is observed that the deformation peaks appear approximately in the lower third of the statistically evaluated deformation range, meaning that the test site experienced a great number of small deformations but only few large ones.

In winter a different pattern is seen. The deformation diagram shows 2 peaks. The one at 2pm is missing corroborating the WIM diagram in which the third peak is less prominent

A comparison of deformations at various depths shows a similar pattern where the three peaks are visible and vary mainly in range, shape and intensity of the peaks.

In conclusion it was indicated that measuring the deformation basin was difficult. However deformation measurements can be used as a statistical fingerprint to be compared with load data. The results indicate that measuring vehicles with GVW greater than 3.5t can be useful for pavement deterioration monitoring.

Simplified site specific models for determination of characteristic traffic load

Eugene O'Brien reported on how to define a simplified site-specific traffic loading model. Although current methods of load assessment are improving, they require considerable amount of data and they turn out too complex for everyday assessment. A simplified site-specific model is required. This model should be easy to use, involve a minimum of statistics and match reasonably well more sophisticated (and accurate) models.

In the design stage, traffic load models are conservative due to the uncertainty of future loading conditions and the relative low cost of adding extra capacity. However, when assessing an existing bridge, the approach should not be as conservative, since the cost of strengthening/replacing a bridge is very high and the current loading can be measured and monitored.

Histograms of truck weights collected on a number of real Weigh-In-Motion sites are used to compare the simplified site-specific model to a more complex statistical approach. A bi- or tri-modal Gaussian distribution is fitted to the available weight histograms. Then a Monte-Carlo simulation is used to generate traffic weights and many different truck events on a bridge. The load effect is fitted to an Extreme Value Statistical Distribution and the characteristic value is finally found. The characteristic value changes considerably for each WIM site.

A simplified traffic model consisting only of 5-axle truck meeting events is proposed herein. Characteristic shear and moment values are determined for 4 WIM sites and 5 bridge span lengths using the simplified traffic model (only 5-axle trucks) and all trucks. It can be seen how the loss of accuracy when using only 5-axle trucks compared to all trucks is very small.

Site-specific traffic loading models can be calculated for bridges using elaborated statistical models. An alternative simplified model, easy to implement, has shown to achieve accurate load effects for a combination of WIM sites and span lengths when compared to a more elaborated model.

Analysis of traffic load effects on railway bridges using weigh-in-motion data

Gerard James reported on two mathematical methods used in analysing traffic load effects for railway bridges. These methods are based on a Generalised Extreme Value (GEV) distribution and a Generalised Pareto Distribution (GPD). Both GEV and GPD approaches extrapolate the available data to obtain the return load (a loading event with a very small risk of occurring) and provide the distribution of the load effect for reliability applications.

In the traditional analysis method, small discrepancies in the estimation of the parent distribution can lead to large errors for the distribution of maximum loading effects. GEV is based on extreme value theory and it takes into count maximums for a sampling period. This method does not have to assume certain family of distributions (i.e., Gumbel, Weibull), although it has the disadvantage of possibly missing significant values within the sampling period. GPD takes into count peaks over threshold. The choice of an adequate threshold has a strong influence in final results.

A railway WIM system consisting of strain gauges attached to the railway tracks was used to obtain information on wagon or loco type, speed and static axle force of the train. 7400 trains were registered during 4 months of measurements. Then, dynamic simulations of a train over a bridge were carried out to evaluate both statistical approaches. The train was modelled as a moving constant force and the bridge as a one-dimensional beam. The total dynamic response was obtained by modal superposition. The GEV method gave good results except for very short span bridges. For a 10 m bridge, GPD gave a reasonable tail fit and overestimated the return loads, but for a 4 m bridge there was a poor tail fit and return loads were underestimated. Mean values of the return load by GEV and GPD methods compared favourably for 8 and 20 m bridge spans.

Two extrapolation mathematical methods that don’t require a prior knowledge of the tail behaviour have been presented. The methods allow evaluating uncertainties associated to parameter estimates. The data fits well to the mathematical models except for very short span bridges, possibly due to erroneous high axle load measurements. An accurate evaluation of extreme load effects requires long measuring periods and time-consuming dynamic simulations.

Slovenian experience in using WIM data for road planning and maintenance

Brozovic reported on the results of 30 WIM sites that were established to cover all major routes in Slovenia and weigh all vehicles over 3.5t. The paper focuses on using bridge WIM which uses the superstructure of the bridges as a measuring platform in contrast to pavement WIM that is placed within the top layer of the pavement. The bridge WIM essentially uses strain gauges to measure the deflection of the structure and in combination with speed and axel distances of the vehicle calculates the axel loads and GVW. This system has higher accuracy, is non intrusive to pavement and traffic, and can easily be installed and moved. The measurements are taken twice yearly and each time for seven days. The WIM data is converted to ESALS and results are used in Slovenia mainly for traffic planning and on a limited basis for pavement design, and bridge assessment.

The proportion of cumulative ESAL values per vehicle category was presented. These results show that in Slovenia almost 60% of the total loading is caused by articulated vehicles while vehicles less than 3.5t contribute less than 0.1% and can be neglected. It was noted that number of overloaded vehicles does not indicate the real amount of overloading and examples were given to that effect.

The accuracy of the system was calculated according to COST 323 specifications. The majority of the measurements fell into accuracy classes B(10) and C(15) with these values decreasing in cases of bumpy approaches to bridges.

The potential for using high speed WIM for enforcement was presented as currently only 0.5% of all overloaded vehicles recorded through WIM are fined using static scales. Applying a higher threshold for accuracy would increase this number to 45% which could result in a substantial increase in revenue.

Discussion following session 5

Chai-Pei Chou shared the experience in Taiwan indicating that there is a linear relationship between the number of axels and the ESALS when plotted with the slope varying depending on the site. James indicated that the accumulative loading can be used in a similar fashion as his approach with ultimate limit state, for fatigue loading. Similarly taking into account a form of traffic growth was considered useful. The simple model could be expanded to a 3-D FE model. It was agreed that it is extremely important to use long term data for any extrapolation.
It was indicated that no permanent rail WIM sites are currently used in Slovenia. The bridge WIM system shown from Slovenia is a portable system which requires recalibration after 6 months.

Discussion transcription

<u>Discussion following presentation by Eugene O'Brien (UCD, Ireland):</u>

Ales Žnidarič (ZAG, Ljublana): Can you explain why you took only span about 15 m because if you go lower those differences between 5-axle trucks and shorter trucks will come into play?

Eugene O'Brien (UCD, Ireland): The study is limited to that short- medium-span range. If you go to larger spans, you are going to get traffic jam effects and it is another study, more work required to find the appropriate values. And if you go shorter the weight of the tridem is quite important and we assume a mean distribution between axles of the weights. So we pick the gross weight proper to the site. Then, we assume the distribution of weights between axles is the same for the site. This is an assumption I would be nervous about in the very short spans. I think in the shorter spans you need to look at the tridem weights a little more closely.

Ales Žnidarič (ZAG, Ljublana): Double weights as well as they can be even heavier than tridems.

Eugene O'Brien (UCD, Ireland): Yes.

Mark Gardner (Fugro Consultants LP, USA): I was wondering if you had analysed the sensitivity of your simplified method to relative accuracy of the WIM measurement.

Eugene O'Brien (UCD, Ireland): No, we haven't done that. Alan O'Connor has done some sensitivity studies for the detailed statistical method. There are sensitivities and work to be done. So, I would say that getting away from the simplified method and looking at the statistics, statistical methods are quite sensitive to the data. If you take 4 weeks of data and you picked up the following year, you might get quite a different answer using current techniques, so there is work to be done there and we are involved in that.

Discussion following presentation by Gerard James (KTH, Sweden):

Bernard Jacob (LCPC, France): I have a question on the load return period. First of all, the terminology seems to me a bit strange because you talk about load return period. I don't know exactly what you mean. Load within a given return period means that the mean interval of time between two level crossing or exceedance of the load is the return period. Now my question is "you show some value of the return load: 50 or 100 years". If we take 50 years, return period means that for example, with a probability of exceedance of 5% the return period would be 2 years for the lifetime for return period of 50 years. And if we consider lifetime of 100 or 50 years for the bridge with a 5% probability of exceedance the return period comes 1000 years. So, what's the real value you have?

Gerard James (KTH, Sweden): I am talking about the mean value so I am not talking about any percentage around that. It is the mean value of the return period for this load level that is a 5%.

Bernard Jacob (LCPC, France): So I suggest you change the terminology maybe.

Gerard James (KTH, Sweden): OK. There is a difference between highway bridges and railway bridges, because we tend to use this 5% on 100 years. Going up to 1000 years seems a bit extravagant in my opinion.

Bernard Jacob (LCPC, France): The value of 1000 years seems extravagant if you have in mind lifetime of the bridge but a 1000 year return period exactly match a 50 years lifetime with a probability of exceedance of the load of 5%, which is not extravagant because exceeding the design load by 5% over 50 years is not extravagant.

Gerard James (KTH, Sweden): I think one of the problems with that is that if you are going to assess bridges using that type of value, it shouldn't have a great effect when you go up to 100 years or 1000 years. It is flat at that stage. I really think it doesn't have a big effect.

Bernard Jacob (LCPC, France): The increase of the load with the return period is logarithmic so I agree with you the difference is not huge but I think we should take into account given lifetime and given risk. And this is two parameters, not only one.

Gerard James (KTH, Sweden): When this is done, we mainly work on mean values of the estimates. Very few people actually work on uncertainties of the estimates. And as you have seen from this presentation, the uncertainties far outweigh the small value considered of 5%.

Ales Žnidarič (ZAG, Ljublana): I think we should not forget when we do assessment we actually don't do it for 50 years because conditions can change so it is usually prescribed for what period you are doing this.

Gerard James (KTH, Sweden): That's true as well. That's one of the reasons I was putting down it might be 10 years as well. As for an old bridge you might be interested in keeping in service for 10 years.

Questions to Gerard James (KTH, Sweden) and Eugene O'Brien (UCD, Ireland) at the end of Session 5:

Mark Gardner (Fugro Consultants LP, USA): Question for Eugene O'Brien and Mr. James. Your presentations on the bridge protection seem to focus on the maximum critical loading events. In pavement design we get accumulated damage over time and not maximum loading events. For the application of WIM and traffic data collection, we, in pavement, we are looking at identification of spectra of loading as opposed to the max loading events. I was wondering if there were similar considerations for accumulated damage to bridges as opposed to max loading events.

Gerard James (KTH, Sweden): That comes in serviceability limits states and it is in fatigue of bridges. And absolutely, it can be used, go forward and use distributions to use accumulated damaged in bridges. The thing with extreme values is that we have two different states: one is the ultimate limit state and that is when we need to consider the extreme value distributions.

Eugene O'Brien (UCD, Ireland): It is mostly a problem for steel bridges the fatigure damage. The accumulated damage approach would be relevant for steel bridges in fatigue design. We are not involved in that because Ireland has less than a dozen of steel bridges in the whole country. We are involved in a pavement study in collaboration with the University of Nottingham and we are developing a fatigue model for pavement damage over time.

Bernard Jacob (LCPC, France): I have exactly similar questions concerning fatigue. Fatigue also concerns composite steel and concrete bridges and there are a lot such bridges. I would say that for fatigue the influence of the load is much bigger. If you increase the load volume and the load intensity by 10 or 15%, then the effect on the bridge lifetime or the cost is much more than for the extreme value, so did you carry any study for fatigue of railway bridges?

Gerard James (KTH, Sweden): I personally haven't had any such an evaluation. I think it would be an interesting step to go forward to make some form of fatigue calculations since the information is there.

Arturo González (UCD, Ireland): In the statistical approach for the extreme value, do you allow for traffic growth in your models? And if you don't, aren't we taking too many chances and shouldn't we require a continuous monitoring of the bridge to allow for a change in the traffic conditions?

Gerard James (KTH, Sweden): That's definitively an aspect if you wish to include some conservatism and it is bound not to be a steady state. Of course, you can include some form of allowance for some growth, but I haven't done it.

Eugene O'Brien (UCD, Ireland): You can monitor the bridge. It is not that expensive. And if the traffic is growing, a re-assessment of the bridge is necessary. We are doing a study looking at the potential impact of bigger trucks would made on the design and assessment of bridges. There is some discussion perhaps if the 6-axle truck will become more common in Europe and it will replace the 5-axle truck over time, so we are going to investigate how that is going to affect our bridges.

Arturo González (UCD, Ireland): You have used for 4 meters, 8 meters and 20 meters span bridges a very simple dynamic model with only one force that is not realistic because you can not neglect the mass of the moving load compared to the bridge. Do you know the implications of using a more realistic 3-D model for a traffic Monte-Carlo simulation, i.e., trying to obtain the parameters for the vehicles?

Gerard James (KTH, Sweden): It wasn't just one axle on the bridge at a time. It depended on the axle configuration so they were driven on the bridge with the actual spacings, so the whole train has been driven over. I agree with you the model is extremely simple but if we are using bridge weigh-in-motion systems we are getting load effects directly and then, we don't have to do this dynamic modelling and you can go straight to extreme value distributions or some fatigue analysis. But I agree the model is very crude.

T. Ojio (Nagoya University, Japan): I would like to make a question to the two presenters on the statistical load model. Which are the advantages of using a statistical model using real data from WIM? Because traffic data from WIM is not histogram, it is real data, the sequences are site-specific.

Gerard James (KTH, Sweden): The main problem is that if you have relatively short monitoring, perhaps just a few months of data, and you have to decide what's going to happen with a extreme small probability of it happening in the ultimate state, so you have to look a characteristic load with an extremely low probability of occurring. And you only have a very small amount of data to do that, so you have to extrapolate. In some way, you have to fit some form of statistical distribution to your data to be able to extrapolate.

Eugene O'Brien (UCD, Ireland): I would agree. The critical loading event for many short-span bridges is when two trucks meet and the number of meeting events you would record in a bridge monitoring system is not enough for a decent extrapolation. So you need to collect enough WIM data to do that and then simulate a lot of meeting events and you get an increase in the power of data in that way.

T. Ojio (Nagoya University, Japan): On National highway in Japan, maximum load is not a commercial vehicle but it is a special type of vehicle: truck train of about 160 tonnes for 6 axles.

Eugene O'Brien (UCD, Ireland): We would have a similar situation. The statistical studies are arriving to what in Europe is the normal load (extreme situation), and we also consider abnormal loads (a 180 tonne vehicle in UK and Ireland). We design for that separately.

Bernard Jacob (LCPC, France): I fully agree with the remark of our Japanese colleagues because you underlined extrapolation methods are very sensitive to the statistical distribution. In LCPC we developed for road bridges a system which can collect data for a long-term period, like one or two years. Not WIM data, but load effect data or strain. We stored the load maximum effects, but only the peak values and the level-crossing histograms in order to compare after the long-term period like one or two years of measurement with the extrapolation from the basic model and the measurement for longer time period. It is extremely important to carry some long-term measurement before doing extrapolation. Because we have some experience that extrapolation can be completely crazy in some cases. In you make measurement for one week or one month, you might have some particular conditions and even you can't see long-term period in the system. So I recommend for road or rail a long-term measurement.

Gerard James (KTH, Sweden): I would agree with you. You always prefer more data when you do this extrapolation. You don't feel comfortable with four months of data that to say that the events are very unlikely happen. However, in the rail situation, it is a lot easier than in a road situation. You can expect that traffic doesn't change that much. Even weekly or monthly basis, you have the same type of traffic on the rail, you know exactly where they are. In Sweden at least, you often have single rail traffic, so you don't have problems with meeting events. Rail is a lot easier situation than the road.

Eugene O'Brien (UCD, Ireland): I would agree with Mr. Jacob. It is very important to have more data. The more we do this, the more we realise how sensitive the answers are to the data we use. I think that the work that Gerard has done developing the covariance matrixes is very useful because this gives some indication of the variability of the answer you get. And then you can build a margin of safety. And if you have less data you need more margin of safety.

PANEL DISCUSSION 1: USE OF WIM DATA AS A TOOL FOR ENFORCEMENET

Bsc Civil Engineering. Worked as research assistant at the Road and Railroad Lab. of the TU-Delft. Since 1991 at the Road and Hydrauilc Engineering Institute as projectmanager and since 1999 as head of the Pavement Loading and Winter Maintenance group. Mr. Henny is responsible for the development and implementation of WIM-systems at the Dutch motorways. Member of the Scientific Committees of all IC-WIM conferences.

Dr. Chia-pei Chou obtained both Master and Ph.D. degrees from University of Texas at Austin, and specialized in highway and airport pavement design, management system, heavy vehicle sizes and weighs, weigh-in-motion application and the integration of commercial vehicle operation and ITS. She started her teaching career in 1989 and currently is a professor of Dept. of Civil Engineering of National Taiwan University and serves as the Director of Centre for International Academic Exchanges of NTU.

R. HENNY
Road and Hydraulic Engineering Institute,
Delft, The Netherlands

C. P. CHOU
National Taiwan University
ROC

Panelists:

Chia-Pei Chou, TNU, Republic of China (Taiwan)
Mark Gardner, Fugro Consultants LP, United States of America
Ronald Henny, DWW, The Netherlands
Bernard Jacob, LCPC, France (on behalf of Yves Marchadour, Ministry of Transport)
Chris Koniditsiotis, Austroads, Australia & New Zealand
Hans van Loo, DWW, The Netherlands
Ralph Meschede, BAST, Germany

Summary by Chair and Co-chair

Thorough discussion was conducted during the panel discussion. Reached consensus are listed as follows,

1. Tolerance: To fully utilize weigh-in-motion system for law enforcement, the collected data should be repeatable, traceable, and with legitimate certification, besides, a rational tolerance would be essential. A measurement methodology should be provided to the related authorities with the content of appropriate calibration technique, deviation at different speed, temperature influence, road profile, and inaccuracy.
2. Communication: Technology development of WIM system is already mature enough for enforcement but the communication/education with the government and legal bodies needs to be enhanced. Legal base serves the first priority for WIM enforcement.
3. Education: Given the fact that WIM is a totally new concept of measurement, education should be conducted prior to the enforcement. Education should be conducted to many parties such as truck companies, police, public, lawyers, etc.

4. Integration: To fully utilize the benefit of WIM enforcement system, it is important to integrate the hardware and software of WIM altogether. The software includes not only the computer program but also the signal system.
5. Utilization: WIM data may serve as prescreening mechanism for overload less than 10% of weight or direct enforcement mechanism for overload more than 10% of weight. For trucks with less than 10% overload, the final citation will be issued according to the gross weight obtained from static weight.
6. Strategy: To achieve the win-win situation between the operator and legal system, incentives and comprehensive operator audit system should take place.
7. Economy: Further study on optimal location (highway/main road), ratio, cost, and quantity of WIM system as well as fine for violation is necessary.
8. Practical study: A study on practical high-speed WIM enforcement should be conducted within 6 months to better understand the gap between the suggested approach and practice.
9. Future planning: Impact force measurement should be developed to reduce the damage.

PANEL DISCUSSION 2 : FUTURE APPLICATIONS OF WIM INCLUDING RAILWAY WIM

Professor of Civil Engineering at University College Dublin, Ireland. Vice-chair of COST323 (WIM), delegate for COST345 and COST341. Member of WAVE and SAMARIS projects. Member of Scientific Committees of 1st, 2nd and 3rd WIM conferences.

E. J. OBRIEN
University College Dublin
Ireland

Graduate in Electro technics and economics, the last at the University of Amsterdam. Within ProRail responsible for track access charging.

G. DEN BUURMAN
ProRail
The Netherlands

Panelists:

Gerlof Den Buurman, ProRail, The Netherlands
Victor Dolcemascolo, LCPC, France
Gerard James, KTH, Sweden
Eugene OBrien, UCD, Ireland
Barbara Ostrom, Mactec, United States of America
Lily Poulikakos, EMPA, Switzerland
Hendrik Van de Graaf, NedTrain Consulting, The Netherlands
Aleš Žnidarič, ZAG, Slovenia

Summary by Chair and Co-chair

Many new applications are emerging for WIM technologies and WIM data. There was a wide ranging discussion in which some of these were discussed. Railway WIM was a feature of ICWIM4 for the first time in the conference series. It was generally agreed that the railway WIM problem is easier to solve as there is less variation in the range of vehicles travelling on the track and a rail is a suitable component for instrumentation. There is also no possibility of transverse variation in the position of the vehicle when it passes a sensor. On the other hand, there are issues of electrical interference due to electric trains and the resulting induced currents. Generally however, railway WIM seems to have a distinct advantage over road WIM and new applications of the sensors are already emerging such as wheel flat detection and integration into network management systems.

Aeroplane WIM was also discussed. It was noted that all larger aircraft have on-board weighing systems. However, while there seems to be little interest from the industry, it was generally agreed that aeroplane WIM would be of great benefit. For military aircraft, all trucks carried on board are weighed in advance in order to plan the distribution of weight. For passenger aircraft, this may not be necessary as the variation in the weights of individuals may not be important. However, there is an important application in pavement design. While on-board systems may give the weight of each aeroplane, it requires a WIM system to assemble statistical data on what distribution of axle weights is carried by the taxiway pavement. It was noted that aeroplanes apply less force on a runway during take-off and landing and that the critical locations are more likely to be the taxiways at which stage there is no benefit from aerodynamic lift and there can be significant vehicle bounce.

There was some discussion of road pricing of heavy vehicles. It was reported that this has already been implemented in two European countries, Germany and Switzerland and it seems likely that others may follow. At present, vehicles are charged in accordance with the number of axles, regardless of their weight or even whether they are loaded or unloaded. This is an obvious application area for WIM and there was no disagreement between delegates that vehicles are likely to be charged by weight in the future.

Safety was discussed as a new area where WIM technologies will find an application. Vehicle rollover was talked about as an important safety issue for heavy trucks and WIM data can be used to provide warnings to drivers at risk of overturning. Stability of trucks in very windy areas was also discussed. It is possible to allow heavier trucks to travel over windy bridges for example while lighter empty trucks may not be safe. This would represent a significant improvement over the current situation where all trucks are stopped when wind speeds exceed a certain level. It was pointed out that in Taiwan, overload control has greatly improved safety on the motorway network. While the number of accidents may not have been reduced, the number of fatalities has been reduced significantly by reducing the numbers of overloaded trucks.

There was consensus that there will be integration of sensors systems in the future as WIM systems become part of intelligent transportation systems.

ICWIM4 CONCLUSIONS

Chairperson: E. O'Brien

CONCLUSIONS OF 4TH INTERNATIONAL CONFERENCE ON WEIGH-IN-MOTION

Professor of Civil Engineering at University College Dublin, Ireland. Vice-chair of COST323 (WIM), delegate for COST345 and COST341. Member of WAVE and SAMARIS projects. Member of Scientific Committees of 1st, 2nd and 3rd WIM conferences.

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Abstract
This paper gives a report on the 4th International Conference on Weigh-in-Motion. Highlights are presented of papers presented and views that emerged in Session and Panel Discussions. Predictions are made for the state-of-the-art that will exist in the 5th conference planned for 2008.

Keywords: WIM, Weigh-In-Motion, application, conclusion, summary.

Résumé
Cet article présente le rapport sur la 4ème conférence internationale sur le Pesage-en-Marche. Des points importants ont été abordés dans ces articles, à la suite des discussions de session. Des prévisions sont faites à partir de la situation actuelle, et seront traiter dans la 5ème conférence prévue pour 2008.

Mots-clés : WIM, Pesage–En-Marche, Application, Conclusion, Sommaire.

第四屆國際動態地磅研討會結論

摘要
本篇文章爲第四屆國際動態地磅研討會之報告，內容著重在會中報告之文章以及各場次與小組討論中所達成之觀點。文章中並針對將來 2008 年第五屆動態地磅研討會時之技術發展狀況進行預測。

關鍵字：動態地磅、應用、結論、摘要

1. Introduction

The ICWIM conferences are useful benchmarks for the state-of-the-art in WIM research and development. In 2005, many things have changed since the last WIM conference in 2002. There have been some new completely new technological developments – including a new WIM sensor – as well as improvements in existing technologies. There have been significant developments in existing applications of WIM data and there are important new applications. Integration has been a common theme – WIM systems are in many cases being integrated into wider networks of intelligent transport.

Weigh-in-Motion continues to grow. Sensors and systems are now better – they have come a long way from the early days when road authorities complained about poor accuracy and even poorer durability. Application areas are also growing. Techniques for applying WIM data – such as for bridge assessment – are maturing and becoming better established. New application areas are emerging. For example, direct enforcement of overload now finally seems possible. Some highlights of these developments are summarised in the following sections.

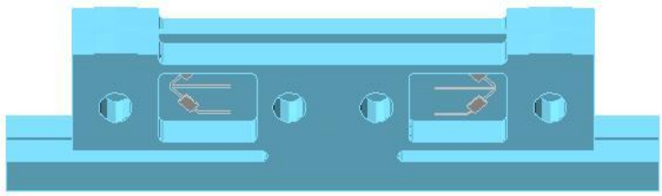
2. Technological Developments

There have been many technological developments since the last international WIM conference in Orlando in 2002. A new multiple-sensor WIM site is operational in the Netherlands as illustrated in Figure 1. It is planned to use this for high-quality pre-selection for overload enforcement in the short term and for direct enforcement long term.

Figure 1 – Multiple-sensor WIM in the Netherlands

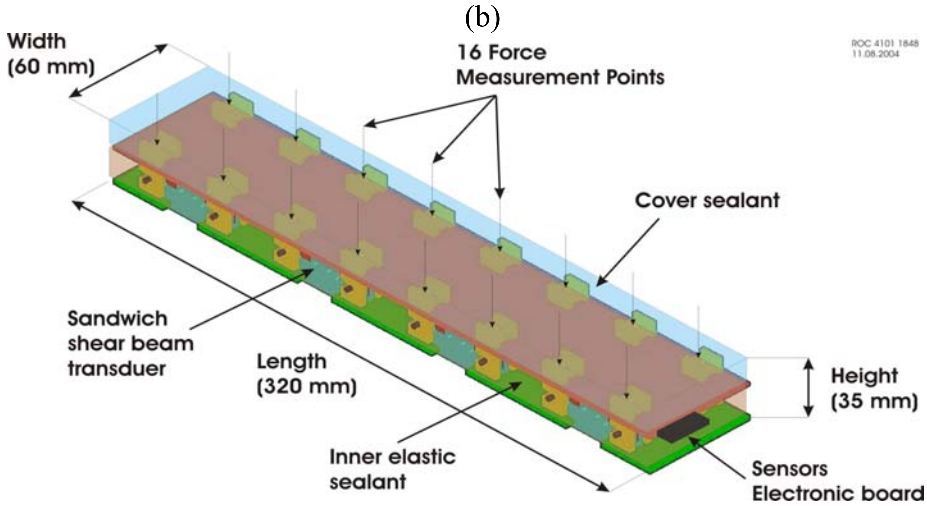
An instrumented vehicle is operational and capable of calibrating the system for dynamic as well as static forces. Papers were also presented at the conference describing French plans for multiple-sensor sites. The proposal is for a similar approach of high-quality pre-selection in the short term with a view to moving to fully automatic enforcement in the longer term. There were papers describing simulation studies to calculate the optimal number of sensors and the best spacing between them. There was also a presentation of a new algorithm for processing the output from multiple sensors. Gonzalez discussed the limitations of neural networks for this purpose and proposed a functional network as an alternative. Results to date would appear to be little better than a simple averaging of the sensor outputs. However, there is a need for further testing with field data and there is potential for significant improvement through further development of the concept.

One of the most significant technological developments reported in ICWIM4 was the new "Integrated Matrix" WIM sensor concept based on strain gauge technology (Figure 2) introduced by Opitz. In contrast to the conventional bending plate, this sensor strip consists of 16 individual shear deformation elements. Opitz reported very small movements and stainless steel material, both of which should be good for durability. A modular system is proposed to facilitate easy maintenance and replacement. A prototype is in existence but it seems likely to be some time before the new system comes into mainstream production.



(a) Basic sensing element based on strain gauge sensing of shear deformation

(b)



(b) Strip sensor matrix of 16 sensing elements

Figure 2 – Integrated Matrix WIM sensor

Poulikakos discussed the use of “stress-in-motion” sensors in an experimental installation. This gives much more information on pavement deformation than a conventional piezo-quartz WIM sensor. Pavement deformations were presented in a useful 3-D histogram format as illustrated in Figure 3. Contours of frequency give an immediate visual impression of what level of deformation is the most frequent and at what times of day these occur.

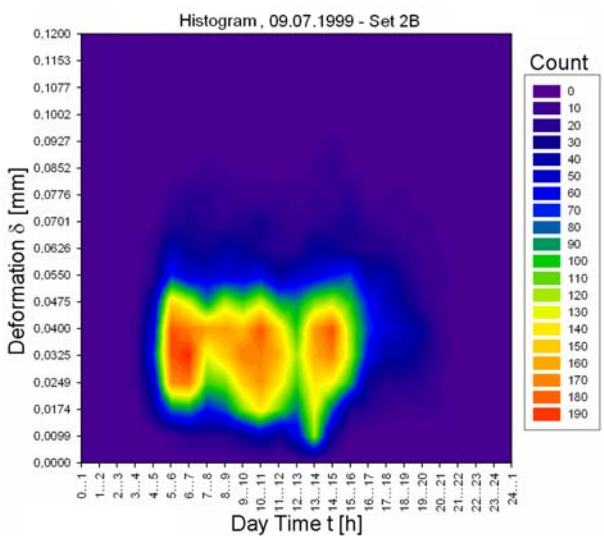


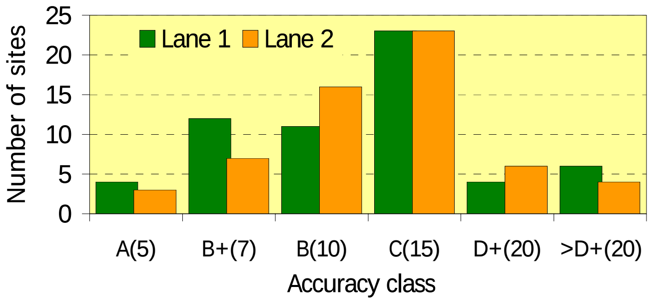
Figure 3 – Example of a Daily Deformation-3D-Histogram at 12 cm Pavement Depth

In another technological development, Labry reported the results of a series of tests of edge effects in two piezoceramic sensors. She showed evidence to suggest that there are bending as well as direct bearing pressure effects in such sensors and proposed a simple formula to correct errors caused by this effect when vehicles travel close to the edge of sensors. This seems like a useful development and she showed the improvements in accuracy that resulted. It would be of great value if this approach could be further tested and extended to other sensor types if appropriate.

Bridge WIM (B-WIM) continues to develop. While a prototype system was on display in ICWIM3, the fourth WIM conference heard about extensive application of commercial B-WIM systems in a number of countries. There is now considerable field experience and a significant number of installations are achieving Class A(5) and Class B+(7) accuracy as can be seen in Figure 4. This is despite the fact that a large proportion of installations have no axle detector on the road (NOR – Nothing On Road).

Li presented a paper by Dunne and others on the use of wavelets to improve the range of bridges for which NOR B-WIM can be applied. The technique was shown to effectively identify all axles in numerically generated signals, even when 10% random noise is present. He also presented preliminary results from field trials using measured strain data for which the technique appears to work well. There was some discussion as to whether the system could work in real time. Subsequent to the conference, the authors reported an execution time of approximately 270 seconds for each signal using a Pentium 4 computer with a 1.4 GHz microprocessor speed and 256 MB RAM.

(a) Strain transducers on a bridge in Poland



(b) Histogram showing numbers of sites achieving COST 323 levels of accuracy

Figure 4 – Bridge Weigh-in-Motion

In most cases, Bridge WIM is currently used as a portable system but it was reported that one system has been in place for three months and there would appear to be no reason why permanent BWIM installations may not be used in the future. A new BWIM system was reported in Sweden with trials on a railway bridge. While good accuracy was reported, there was some discussion about the benefits of instrumenting a bridge when instrumentation of individual rails would be likely to give excellent results.

3. Advances in Existing Applications of WIM

The fourth WIM conference saw many advances in the applications of WIM. A range of existing applications that had been reported at previous conferences have improved in ICWIM4.

3.1 Overload Enforcement

The overload enforcement application featured strongly with a full session of papers. Company profiling, where freight companies whose drivers are consistently violating legal limits are contacted to discuss the issue, was first reported from the Netherlands in ICWIM3. This approach is now working well and has been adopted in other countries with good success.

There were reports of extensive applications of pre-selection and increasingly sophisticated communications between the pre-selection scales and the enforcement authorities. Plans are well advanced for fully automatic overload enforcement, particularly in the Netherlands, where WIM experts are working closely with the metrological and enforcement authorities. At the present time, accurate pre-selection is seen both in the Netherlands and France as an intermediate stage on a path leading to fully automatic enforcement in the medium term. It is not clear yet what level of accuracy will be required for automatic enforcement. It has been suggested that Class A(5) would be sufficient. However, it remains to be seen if this will be acceptable to metrological authorities. It was pointed out that fully automatic overload enforcement has been achieved in the past in Taiwan but this was with a tolerance margin of 20%.

Figure 5 – Instrumented Calibration Truck

The Dutch delegates reported that their 8-axle calibration truck – Figure 5 – is nearly at the stage when it may be approved by the metrological institute. This is fully instrumented and has known dynamic as well as static forces. Hence, any calibration bias due to its pattern of spatial repeatability can be removed to give an improved calibration over what would be achieved with one statically weighed truck alone.

Van Loo presented a paper on the European Union *REMOVE* project. This is a first step towards a harmonised pan-European approach to overload enforcement. The partnership includes police authorities and the emphasis is not on the technical issues but rather on the legal and enforcement issues associated with the problem. This seems likely to be the start of a new era in the automatic enforcement of overload using WIM technology.

3.2 Existing Applications in Infrastructure Assessment and Design

There were significant advances in the traditional application areas of WIM data: bridge and pavement design and assessment. Bridge load assessment continued to feature in ICWIM4. This application area is achieving some degree of maturity and OBrien presented a simplified method of traffic load assessment for road bridges suitable for use by non-specialists. James presented a paper on the assessment of railway bridges. There was considerable discussion on the sensitivity of the result to the accuracy and extent of the WIM data. It was generally agreed that results are quite sensitive and it seems likely that calculated characteristic load effects using two to four weeks of data, as has been suggested in the past, are unreliable. James presented a method in which the variability of the result is taken into account by calculating a characteristic value of the characteristic value of load effect.

In a keynote paper written by Gillman, Gardiner reported that American adoption of axle load spectra for pavement design instead of the traditional equivalent standard axles, has resulted in a significant increase in the demand for WIM data. This will result in increased data collection costs but must surely lead to savings in the long term due to improved accuracy in pavement design calculations.

4. New Applications of WIM

Many new applications of WIM data were reported in ICWIM4. There was a full session on Railway WIM. It was agreed that this is technically less challenging than road WIM as the vehicles are less varied and their transverse position is fixed. Furthermore, the rail lends itself to instrumentation with strain sensing devices. De Graaf described a railway WIM system that utilises fibre optic sensors. This has the advantage of being insensitive to induced currents from electric trains. The accuracy of railway WIM appears to be good although there were no reports of independent tests. Den Buurman reported excellent results from using WIM sensors to detect "wheel flats“. This lack of roundness of wheels is a considerable source of damage to rail track and, with an integrated system throughout the Netherlands, considerable savings in maintenance costs were found. There are plans to count passengers using WIM sensors in the future. This is a difficult challenge as the total weight of passengers is a relatively small percentage of the gross weight of the train.

There was a comment from a South African delegate about damage to thin road pavements by over-inflated tyres. This potential application area of WIM was already discussed at ICWIM3 and Poulikakos reported that there are sensors available on the market to detect under- and over-inflated tyres. However, WIM does not seem to have been used to date for this application.

Aberkrombie described the use of low-speed WIM to weigh trucks before they are transported on military aircraft. This has resulted in considerable improvement in the time taken to complete the weighing process. There was some discussion of aeroplane WIM in general. While most aircraft have on-board weighing capability, there is still a lack of knowledge about the distribution of load applied to the pavement in the airport taxiways.

Truck overturning risk was discussed in the Panel Discussion by Dolcemascolo. With WIM sensors, it is possible to provide a warning to drivers if their weight represents a risk of overturning given local road geometric conditions. In the same discussion, Žnidarič raised the issue of wind forces on trucks. Again, WIM sensors can be used to improve the accuracy of overturning risk warning systems.

4.2 Integration of WIM applications

A number of speakers presented examples whereby WIM sensors are being integrated into wider sensing networks and management systems. Den Buurman described the Dutch railway system where the networking of the data is important in order to identify and repair the particular trains where wheel flats exist. This system is integrated with an energy consumption model and the track access charging system.

Chen described the system in Taiwan where overload enforcement centres are located adjacent to toll stations. This has been found to have considerable advantages in terms of safety and the efficiency of removal of the overloaded trucks. Poulikakos also presented a paper describing an integrated system. In this experimental installation in Switzerland, there are sensors for the monitoring of axle weight, pavement deformation, vibration, humidity, temperature and noise.

5. Forecasts for 2008

The fifth ICWIM conference is planned for Paris in 2008. There will be many further developments and improvements in WIM technologies and applications at that time. It seems likely that railway WIM – Figure 6 – will have become more widespread at that time as the potential benefits of this application area are realised. Fully automatic enforcement of

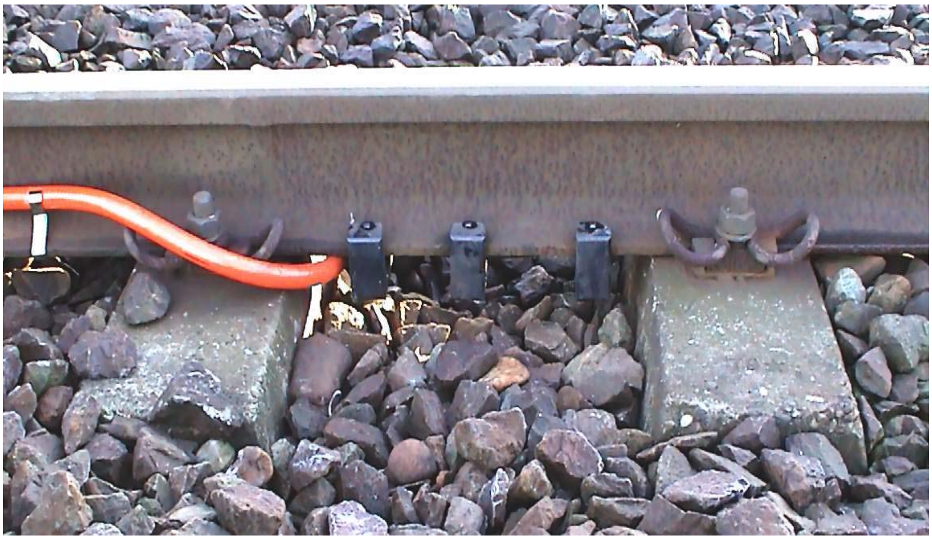


Figure 6 – Railway WIM sensor in the Netherlands

overloaded vehicles is quite likely and there will be considerable further improvements in the efficiency of semi-automatic systems. The Integrated Matrix WIM sensor of Figure 2 should have reached the market by 2008 – it will quite likely be on display in the ICWIM5 exhibition.

It remains to be seen if these predictions come true. What will certainly be true is that there will be further improvements in the accuracy, durability and in the range of applications of WIM throughout the world.

List of Organisations (before February 2005) MAJ?

Arcadis Infra BV	P. O. Box 220, 3800 AE Amersfoort			The Netherlands
Ardin	Boroka U. 8	H-2089	Telki	Hungary
Austroads	C/- National Transport Commission, Level 15, 628 Bourke Street,	3000	Melbourne, Victoria	Australia
Baas R&D b.v.	PO box 57, 2740AB		Waddinxveen	The Netherlands
CESTEL D.O.O.	Špruha 32, 1236 Trzin			Slovenia
CETE de l'Est	1 Bd Solidarité	57076	Metz	France
Direkcija RS ZA CESTE	Tržaška 19	1000	Ljubljana	Slovenia
DONG-A University, Busan, South Korea	Dept. of Civil Eng. Dong-A Univ. 840 Hadan2-dong Saha-gu Busan			South Korea
ECM Asia ITS Co, Ltd	RM203-1, Kayangtechnotown-1487 Kayabg3-Dong	Kangseo-Ku-157-810	Seoul	Korea
EMPA	Überlandstrasse 129	8600	Dübendorf	Switzerland
Fugro Consultants LP	8613 Cross Park Drive	78754	Austin, Texas	USA

German Aerospace Center (DLR), Institute of Transportation Research	Rutherfords 2	12489	Berlin	Germany
INHA University, Incheon, South Korea	Dept. of Civil Eng. INHA University, 253 Nam-gu Incheon	402-751		South Korea
Kistler Japan Co. Ltd	MT Bldg., 7-5, Shibadaimon 2-chome, Minato-ku	105-0012	Tokyo	Japan
Laboratoire Central Ponts et Chaussees (LCPC)	58 bd Lefebvre	75015	Paris	France
MACTEC Engineering and Consulting, Inc.	12104 Indian Creek Court, Suite A,	20705	Beltsville, Maryland	USA
Mikros Trafic Monitoring (PTY) Ltd	PO Box 73852, Lynnwood Rigde	0040	Pretoria	South Africa
Ministry of Transport	P.O. Box 5044	2600 GA	Delft	The Netherlands
Ministry of Works	P. O. Box 9423 Bar rs Salaam			
Nagoya University	Division of Environmental Engineering and Architecture, Nagoya University, Euro-choi, Chikusa-ku	464-8603	Nagoya City	Japan
NedTrain Consulting	Postbus 2016, 3500 Ga Utrecht			The Netherlands

OMRON Corp.	16th Floor Dojima Avanza Bldg 1-6-20	Dojima. Kita-Ku, Osaka 530-0003		Japan
ORNL	1 Bethel Valley Rd, MS-6418, Oak Ridge, TN 37831			
ProRail	P.O. Box 2039	3500	GA Utrecht	The Netherlands
Rigobert Opitz Consulting & Engineering (ROC)	Insterburger Str. 1A	D 76316	Malsch	Germany
Road and Bridge Research Institute	Jagiellońska 80, PL. 03-301, Warszawa			Poland
Royal Institute of Technology, Stockholm	Department of Civil and Architectural Engineering, Royal Institute of Technology	SE 100 44	Stockholm	Sweden
SA National Roads Agency Limited	SA National Roads Agency. P O Box 415	1	Pretoria	South Africa
TDC Systems Ltd.	22 Lynx Crescent, Weston Industrial Estate, Weston-super-Mare, North Somerset, BS24_9 DJ			United Kingdom
The Hong Kong Polytechnic University	Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon,			P. R. China

	Hong Kong,			
Toledo do Brasil Indústria de Balanças Ltda.	Rua Galeno de Castro, 730	04696-916	São Paulo	Brazil
Transport research centre	Lisenska 33a, 636 00 Brno			Czech
University College Dublin (UCD)	Civil Engineering Department, Earlsfort Terrace	2	Dublin	Ireland
UT-BATTELLE/ Oak Ridge National Laboratory	1 Bethel Valley Rd, MS-6418, Oak Ridge, TN 37831-6418			

List of Exhibitors (before February 2005) à MAJ

Captels LS WIM	Z.A.E. des Avants-1, Chemin du Mazet	34270	Saint-Mathieu de Tréviers		France
Central Pacific Co.	Ho-Ping west road Sec 3	284	Taipei		Taiwan
Electronique Controle Mesure	4 Rue Du Bois Chene Le Loup	54500	Vandoeuvre Les Nancy		France
Electronique Controle Mesure Inc.	464 Commercial Drive	78610	Buda	Texas	USA
International Road Dynamics (IRD)	702 43rd St. E.	S7K 3T9	Saskatoon	SK	Canada
Kistler Ltd	MT Bldg., 7-5, Shibadaimon 2-chome, Minato-ku	105-0012	Tokyo		Japan
Measurement Specialties, Inc	460 East Swedesford Rd, Ste 3005	19087	Wayne	PA	USA
Sterela S.A.	5, Impasse Pedenau	31880	Pins-Justaret		France
Vaultage Media	P.O. Box 2156 Templestowe Heights VIC	3107			Australia

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