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Re-Gen

Risk Assessment of Ageing Infrastructure

Guidelines on collecting WIM data and forecasting of traffic load effects on bridges

Deliverable D3.1
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Guidelines on collecting WIM data and forecasting of traffic load effects on bridges

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Executive summary

This report describes guidelines for using Weigh-in-Motion (WIM) data to predict traffic load effects on bridges. Initially, WIM data collection activities are described in the CEDR funding and partners countries (Denmark, Germany, Ireland, Netherlands, UK and Slovenia) and France. It is found that all countries have permanent WIM systems which are collecting traffic load data predominantly on primary roads. The vehicle-by-vehicle records which are required for bridge loading calculation are available in all countries however the UK and Denmark do not have the time stamps to a precision of 0.1 second or less which is ideally required for the assessment of traffic loading. It is found that Slovenia is the only country which systematically uses WIM data for bridge loading applications.

The guideline for best practice when collecting WIM data, the COST 323 (2002) European WIM Specification, is described. This specification provides detailed recommendations for site selection, installation, operation, calibration and accuracy assessment of WIM systems. It is critical that these factors are considered in order to obtain accurate WIM data which is suitable for bridge loading applications.

Guidelines are also given for the identification of erroneous WIM data. Such data occurs to some extent at all WIM sites. This data must be identified and removed from a WIM database before any meaningful assessment of bridge loading can be performed. A set of rules are described for identifying individual erroneous WIM records where unrealistic axle loads or spacing have been recorded. A more advanced Kernel Density approach for identifying erroneous records is also described. This statistical approach estimates the probability associated with all possible axle configurations and can be used to complement the basic set of filtering rules. In addition to individual erroneous records, loss of calibration or calibration drift can also occur. Monitoring of the steer-axle weight on five-axle trucks is presented as a method for identifying calibration problems.

A description of state-of-the-art methods for using WIM data for assessing traffic loading on bridges is also given. An extrapolation approach, where an extreme value distribution is fitted to maximum daily load effects, is discussed. Long run simulations are also described as they offer a more comprehensive approach than extrapolating using statistical distributions. Monte Carlo and Scenario Modelling simulation techniques are described including discussion of the advantages of the alternative methods. Fast approximate methods which can be used to get a quick, yet comparable estimate of loading at a site without knowledge of advanced statistical techniques are also outlined. Furthermore, the NCHRP 683 Protocols for Collecting and Using traffic Data in Bridge Design in the US are detailed as there are no such guidelines for Europe.

Case studies are used to demonstrate the importance of using WIM data for bridge applications. In France, the traffic loading on the Millau bridge was assessed using WIM data prior to construction. The results showed that the calculated loads were significantly less than the regulatory loads. In Ireland, a study which uses WIM data to justify an increase in the legal weight limits for 6-axle trucks is described. The results showed that the legal weight limit for these trucks could be increased from 44 t to 46 t without rendering the currently employed bridge traffic load models as inappropriate. Finally, a case study from Slovenia details the use of WIM data in that country to assess existing bridges where there is concern over structural safety. It is shown that by using WIM data, many of these bridges were found to be safe and significant savings on repair/replacement costs were made.

1 Introduction

1.1 Re-Gen overview

Across Europe there is a need to build an understanding of the external factors that will influence the management of national road networks over the coming 20-30 years. These will include the predicted performance of the assets, projected traffic forecasts, potential impact of climate change and how all of this may be impacted by limited funding. Equally, with demand for a single interlinked European road network, the ability to provide optimised planning and maintenance strategies is likely to become even more important.

The Re-Gen hypothesis is that adopting a network-wide probabilistic risk based approach will provide a scientific structure to (i) ensure safe lifecycle analysis of road assets consisting of bridges, retaining walls and steep embankments and (ii) to inform key decisions regarding prioritised maintenance expenditure. The risk based approach will allow optimised lifecycle performance of the infrastructure, within the context of *evolving traffic demands* and *climate change effects*. The proposed framework considers the different types of risk faced by national road administrations – for example, safety risk, such as structural safety, financial risk, such as that arising from a maintenance backlog, or by managing the increasing demand for emergency repairs, operational risk, commercial risk and reputational risk. This risk methodology can then be used by national road administrations for the development of asset management policies, to communicate with stakeholders and to support funding submissions.

The risk is assessed considering not only the probability of failure of an element/network but also consequences of that failure. As a result, the prioritisation of these structures for repair should be planned based upon the associated risk, where risk is defined as the product of the (probability of failure) × (consequence) of that failure. Such a risk based approach will provide Owners/Managers with the facility to optimise budgets/resources from the perspectives of minimisation of cost, i.e. considering alternative rehabilitation strategies including the do-nothing option, for maximised service life performance, as illustrated schematically in Figure 1.

1.2 Objectives and Scope of Deliverable D3.1

Deliverable 3.1 of the Re-Gen project focuses on bridge infrastructure. One of the key parameters for the risk assessment of ageing bridge stock is the traffic loading. Freight traffic volume and traffic volume, in general, is a) constantly increasing in Europe and b) varies considerably from one country to another (Žnidarič A. , 2015). At the same time, in most European countries, the proportion of bridges that were designed and built in times when traffic loading was considerably lower, exceeds 50% of the bridge stock (source FP5 project SAMARIS D19 (2006)). Many of these bridges will need to be strengthened to carry greater load or posted (i.e. load restrictions imposed). However, the system can be optimised if the true safety of the bridge is known through better understanding of the 'actual' traffic loading situation and risks associated with overloading. This will allow NRAs to make informed decisions to prioritise the maintenance of their bridges. Using WIM data the 'actual' traffic loading can be more accurately assessed, hence guidelines on collecting and processing this data are beneficial.

The recent Heroad report (Žnidarič & Kreslin, 2012) from the 2010 CEDR "Effective Asset Management meeting Future Challenges" call revealed that only a few European NRAs exploit the benefits of realistic traffic loading in bridge safety assessment. Even countries with well-developed and regulated bridge assessment procedures, like the UK, rely on traffic counting rather than on WIM data, which can lead to suboptimal results as regards structural safety of bridges.

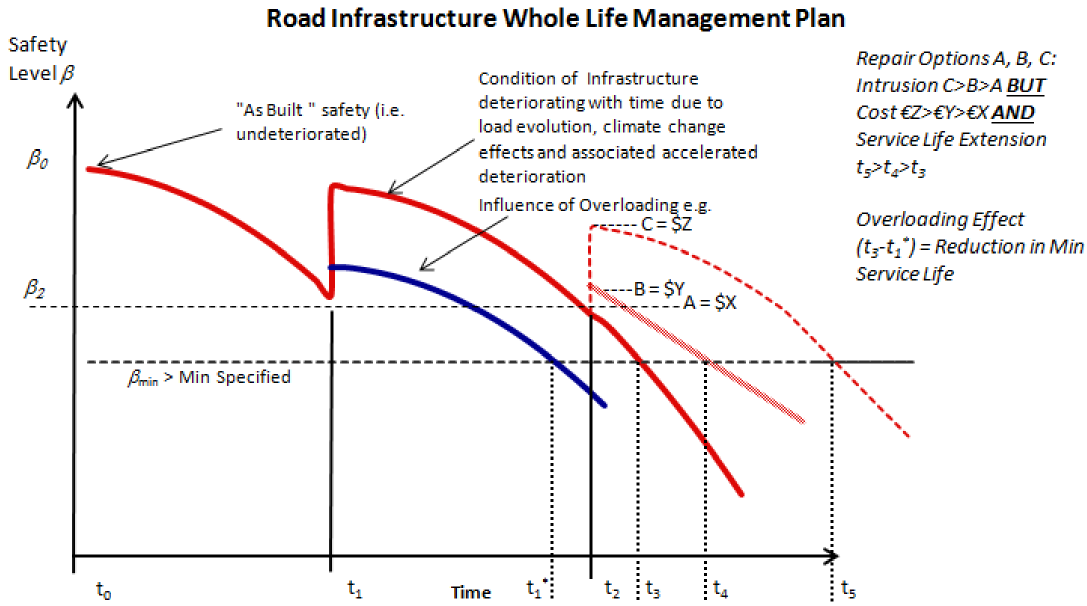


Figure 1: Life Cycle Performance Optimisation

The objectives of Deliverable D3.1 are to:

- provide a state-of-the-art report on the availability of weigh-in-motion (WIM) data in the six funding countries of the CEDR2013 call (Denmark, Germany, Ireland, Netherlands, UK, Slovenia), plus France;
- provide examples of good practice of using WIM data for bridge assessment and provide guidelines on how NRA's can collect and use the data;
- demonstrate with case studies the importance of using WIM data with respect to bridge safety (risks).

In order to meet all objectives, the deliverable contains five chapters. Chapter 1 provides an overview of the entire Re-Gen project and the objectives of Deliverable D3.1. Chapter 2 firstly describes basic information about in-motion weighing and subsequently provides a state-of-the-art report on the availability of weigh-in-motion (WIM) data in the funding countries. It identifies countries that collect WIM data and evaluates this data with respect to location, technologies, collected data and applications. Chapter 3 provides guidelines for collecting and using WIM data for bridge applications which includes procedures for quality assurance and cleaning of erroneous WIM data. Chapter 4 demonstrates, with case studies from France, Ireland and Slovenia, the benefits of using WIM data with respect to bridge safety. Chapter 5 describes the conclusions and recommendations for future activities.

2 Available WIM data

In the following sections a state-of-the-art report on the availability of WIM data in the partner countries (Denmark, France, Ireland, Netherland, Slovenia, UK) is presented. This follows on from Milestone M3.1 of the project (Reliable WIM traffic data information samples from partner countries collected). Initially, a basic introduction to WIM systems is provided. Subsequently a description of the WIM situation for each country follows. Finally, information is evaluated with respect to where the WIM systems are installed, which technologies are used, which data is collected and which applications benefit from WIM data.

2.1 Introduction to weigh-in-motion (WIM)

The most popular devices for collecting information about traffic flows are traffic counters. Counting technologies vary from simple manual checking to rubber tubes, inductive loops and more modern optical and laser devices. Traffic counters are indispensable for collecting traffic flow information, but they do not provide any data about the true axle loads (AL) and gross vehicle weight (GVW) of heavy vehicles.

In order to determine the AL and GVW of heavy vehicles, the vehicles need to be weighed. As illustrated in Figure 2, this can be done in a number of ways - *statically*, *in-motion* or with *on-board weighing* systems.

Static weighing is the most accurate method for weighing vehicles. In most countries, it is the only legal reference to fine offenders who are overloading their vehicles.

On-board weighing systems are installed in individual vehicles and use either load cell technology or pressure readings from air suspension to calculate the weight on the vehicle axles. In Europe this technology is rare, thus this chapter focuses on high-speed weigh-in-motion only. More information on other ways of weighing can be found for example in (Žnidarič A. , 2015).

As illustrated in Figure 2, WIM systems consist of low or high speed systems. Low speed WIM systems are operated in a controlled environment; the speed of the vehicle that crosses the sensors is limited to 5 to 10 km/h and accelerating and braking is not allowed so as to discount the dynamic behaviour of the moving vehicle. High speed WIM systems, often called just a WIM system, are operated at full highway speeds. These systems measure the dynamic axle loads of the vehicles passing at full highway speed under uncontrolled conditions and calculate the best possible approximation of its *static* axle weights. WIM systems typically deliver: axle loads, axle group load, gross vehicle weight, number of axles, length of the vehicle, axle distances, speed and vehicle classification.

1. External structures, either a pavement or a bridge, that serves as the physical framework of a WIM-sensor and transfers the axle loads of the passing vehicles to the sensor;
2. Sensor or transducer that converts the axle load into an electrical signal. The most common sensing technologies are piezo-electric or piezo-quartz materials, strain gauges and fibre optics.

The combination of parts 1 and 2 results in two different types of WIM installations, Figure 2:

- Pavement WIM systems and
- Bridge WIM systems.

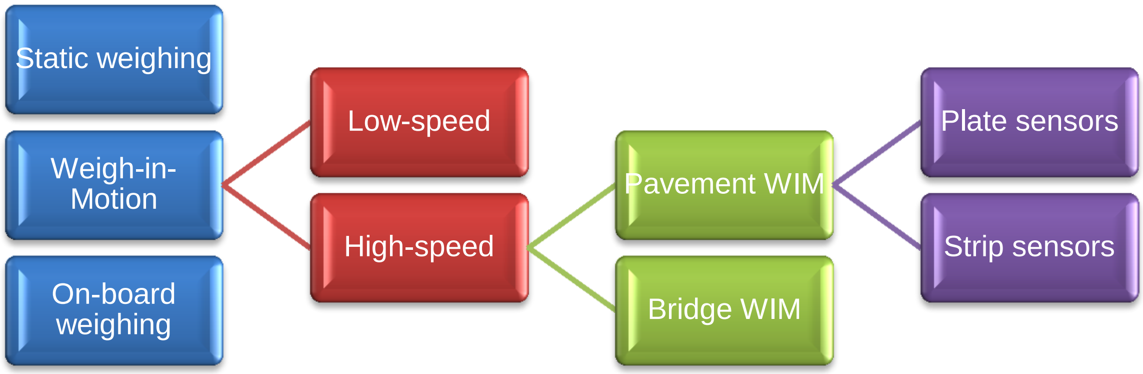


Figure 2: Division of weighing systems

In general a WIM-system can be divided into (FHWA-PL-07-002, 2007):

It should be noted that as long as the results from a pavement WIM system are representative of the loading on the bridge then both pavement and bridge WIM systems can provide vehicle weight data appropriate for bridge load modelling. The difference is that the bridge WIM systems can provide additional information about structural behaviour if they are installed on the bridge that is being assessed.

2.1.1 Pavement WIM systems

A typical pavement WIM installation consists of inductive loops, with a number of WIM sensors in different setups that measure vehicle velocity and detect the type and the length of the vehicles. Based on the width of the sensors, they are divided in two major groups:

- *plate* sensors and
- *strip* sensors.

All pavement WIM systems should be installed on as smooth and flat section of roadway as possible, so as to provide results of expected accuracy (COST 323, 2002).

(a) Plate Sensor (b) Strip Sensor

Figure 3: Pavement WIM Installations

Plate sensors

Their width is larger than the tyre, thus the total axle load is acting on the sensor, Figure 3 (a). Similar sensors are used for static and low-speed axle load measurements. The two prevailing technologies are:

- bending plates, Figure 4, which measure the strain due to bending of a plate caused by a passing wheel and
- load cell devices which, with a number of load cells under the plate, measure forces during the crossing of a wheel.

As a rule, plate sensors provide more accurate results than the strip sensors. However, their installation is more difficult. It cannot be done under traffic and can require a 2-day road closure.

Figure 4: Example of a plate sensor installation

Strip sensors

As the length of the tyre footprint is larger than the width of this type of sensor, only a part of the total axle load acts on the sensor at each time, Figure 3 (b) and Figure 5. In order to capture the total axle load, the signals measured during the passing of an axle over the sensor must be integrated over time.

Today most strip sensors are built around three technologies:

- *piezo-electric* and *piezo-polymer*, Figure 6 (a); both are the cheaper options on the market and are generally less accurate, and
- piezo-quartz, Figure 6 (b); the most common sensor technology today; they are more accurate and stable but also more expensive to purchase and to install.

Strip sensors are typically installed in less than one day, they also do not damage the pavement as much as the plate sensors do.

The main advantages of strip sensors are that they are a proven technology and have relatively high accuracy on smooth road surfaces. Their disadvantages are that road must be closed for installation and maintenance, which is not always easy to do, and that their accuracy suffers as the road surface deteriorates, which happens particularly in flexible pavements (for example asphalt with relatively weak sub-base).

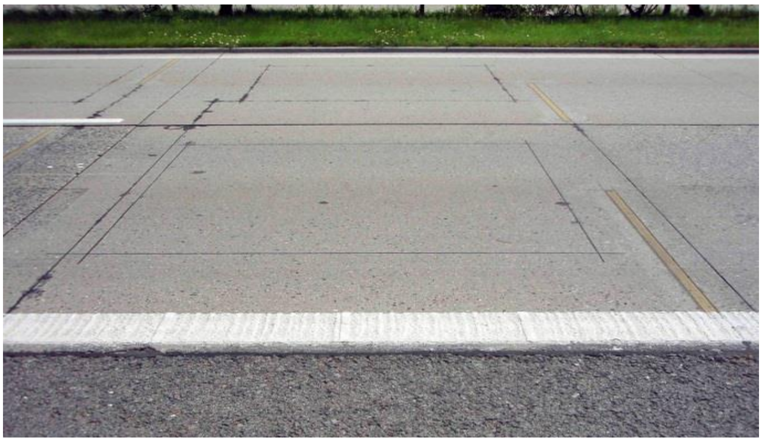
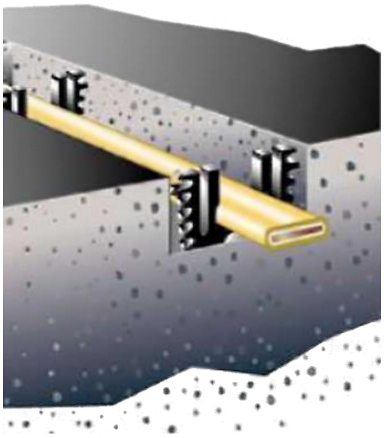


Figure 5: Example of a strip sensor installation



(a) embedded piezo-polymer

(b) piezo- quartz sensor

Figure 6: Cross-sections of strip sensors

2.1.2 Bridge Weigh-in-Motion

Bridge-WIM or *B-WIM* refers to a specific method that uses an instrumented bridge or culvert to weigh the passing vehicles. These systems provide equivalent results to the pavement WIM systems. However, as the sensors are mounted on the soffit of the bridge, Figure 7, for the most part, *road closure during installation is not necessary*.

Since its appearance 35 years ago (Moses, 1979) B-WIM technology has undergone considerable improvements. After being researched extensively in the 1990s (WAVE, 2001), it entered the market in 2002 (Žnidarič, Lavrič, & Kalin, 2002) and is today used in a number of European countries.

The main advantages of B-WIM systems are (OBrien, Žnidarič, & Ojio, 2008):

Figure 7: Bridge instrumentation with strain transducers

- complete portability, without affecting accuracy,
- high accuracy on smooth road surfaces,
- ease of installation, *without interruption of traffic*,
- continuous flow of traffic (i.e. often bridges cannot be avoided, so traffic is likely to actually pass over them), and
- they provide additional structural information (influence lines, load distribution factors, dynamic loading factors) for advanced bridge assessment (Žnidarič & Lavrič, 2010).

The disadvantages are that an appropriate bridge is needed to install the system and that setting up a system on less common structures requires considerable knowledge and expertise about bridges.

2.1.3 Accuracy of WIM data

The weighing performance of any WIM system is determined by the combination of the accuracy and reliability of its measurements. The most common way to describe WIM performance is that it has an accuracy of ±x% for y% of measurements, for example ±10% for 95% of measurements. Accuracy criteria vary for the measurement of single axle loads, axle group loads and gross vehicle weights. For example, for a system intended to achieve Class B(10) according to the European specifications for weigh-in-motion (COST 323, 2002) the errors must be for a specific confidence interval, which depending on the test conditions, for 95% of measurements, is within ±10% for gross vehicle masses, ±13% for axle group loads, ±15% for single axle loads and ±20% for loads of axles within a group.

The actual accuracy of WIM results depends on a number of factors:

- road condition,
- quality of installation,
- maintenance and calibration,
- traffic conditions,
- types of sensors,
- speed of the vehicles,
- temperature effects.

Road condition: Uneven and rutted road surfaces around the pavement WIM installation will excite dynamic response of the passing vehicles and will very likely generate poor results.

Smooth, rigid concrete pavements are more appropriate than the flexible ones. The WIM specifications list criteria for the selection of a good WIM location.

Quality of the installation: For pavement WIM systems, the top of the sensors must be flush with the road surface. Otherwise the sensors will create a bump that will affect the accuracy of the results. For bridge WIM systems it is crucial to avoid cracks in the concrete and to properly attach sensors to the bridge. To mitigate these issues, all WIM sensors and systems should be installed by experienced users or vendors.

Maintenance and calibration: After installation each WIM system has to be calibrated. This is generally conducted using one or more calibration trucks with known static axle loads or by using selected vehicles from the traffic stream. Due to wear and tear on the sensors and possible changes in the road's condition, the behaviour of all WIM systems will change over time. Therefore maintenance and recalibration are required at regular intervals, normally once or twice a year.

Traffic conditions: The traffic flow over a WIM system should be as smooth as possible, as stop-and-go traffic cannot be captured.

Types of sensors: Different sensor technologies each have their own characteristics related to accuracy, stability, durability and price.

Speed of the vehicles: Speed is largely related to the dynamic behaviour of moving vehicles. Generally, the higher the speeds, the more excited the vehicles become (which is particularly true on uneven road surfaces) which will likely lower the accuracy of the measurements.

Temperature effects: Although good-quality WIM sensors are not temperature-dependent, the WIM installations as a whole usually are. This is true for most pavements and some bridge types. If not properly compensated for, the temperature effects can result in considerable errors that vary with temperature. As an example, Figure 8 displays 6 months of the average daily gross weights of the most common heavy goods vehicles in Europe, the 5-axle semi-trailers, collected with a WIM system before it was calibrated for temperature. The values should have been stable over time, but the example exhibits a clear dependence of the average gross weights on temperature that resulted in almost 20% difference in results at 5 and at 23 degrees Celsius!

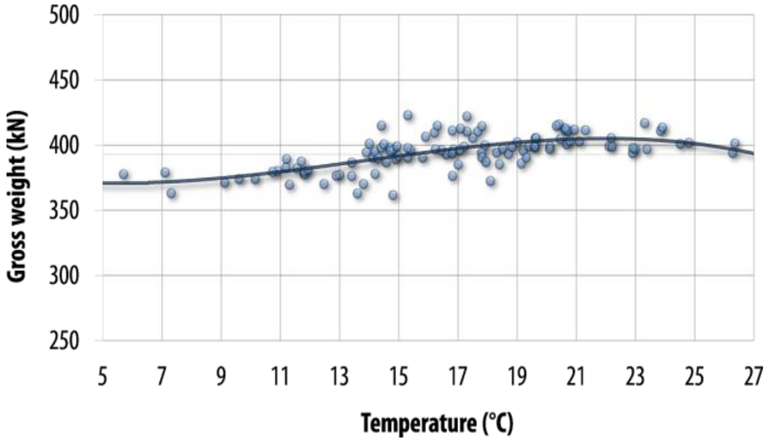
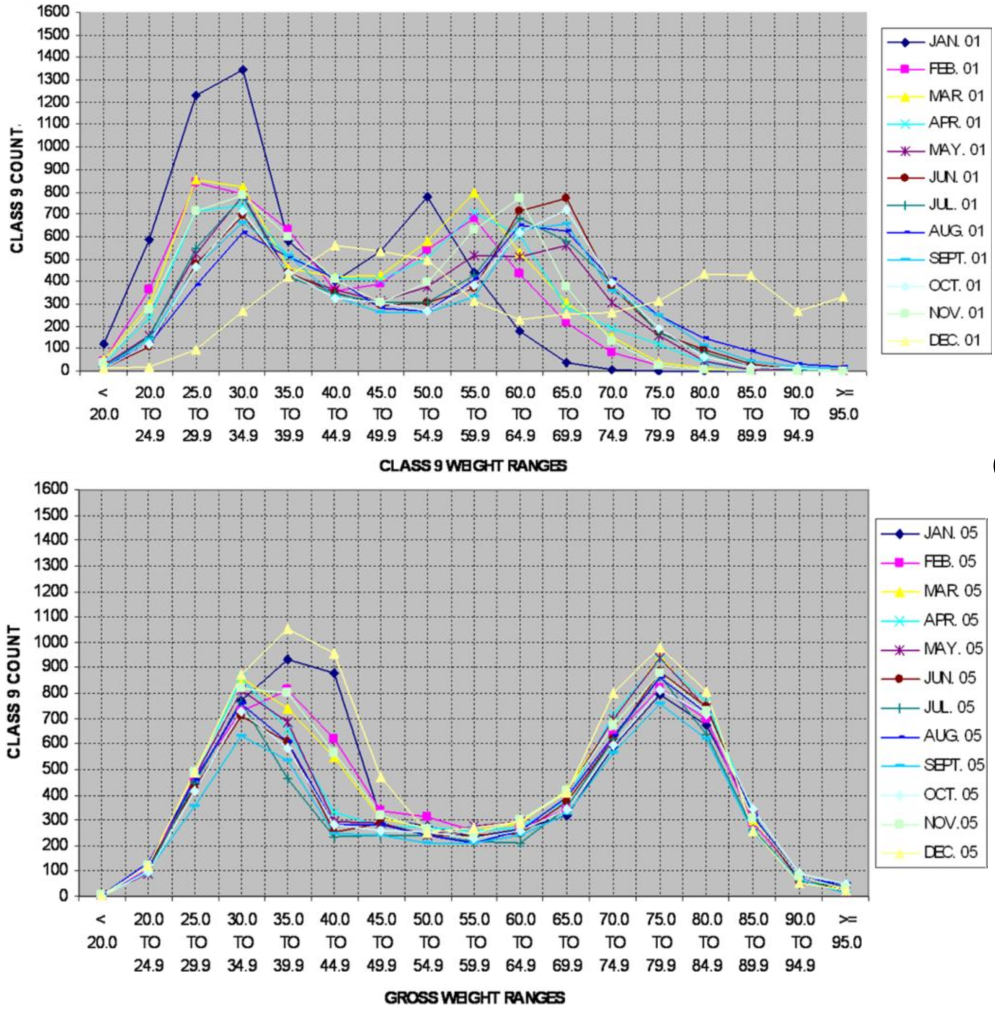


Figure 8: Temperature dependence of median daily gross weights of 5-axle semi-trailers

2.1.4 Quality of WIM data

Most applications of WIM data (e.g. for studies of traffic flows, statistics & planning) rely on the average accuracy of all measurements. The only applications where the accuracy of each individual measurement prevails are direct enforcement and pre-selection of overloaded vehicles.

WIM systems generate an enormous amount of data and if this data is not controlled for quality, it is not usable. Walker and Cebon (2011) describe in their report how attitudes regarding data quality have changed since the beginning of the Long Term Pavement Performance Programme in the US that has collected WIM data systematically since 1992. Even 10 years after the start of the programme many results were disappointing, as can be seen in Figure 9 (a), which displays the monthly distributions of the gross weights of 5-axle semi-trailers from a site in Florida in 2001. The two peaks, which represent the gross weight for empty and fully loaded vehicles, should not move but in this case have shifted by over 30% from the lowest to the highest value. The situation clearly improved in 2005 (Figure 9 (b)) when the new installation specifications were set in place, which among others:



(a)
(b)

Figure 9: Effect of implementation of new installation specifications on LTPP WIM data, from (Walker & Cebon, 2011)

- banned lower-quality piezo-electric cables,
- required:
  - bending plates,
  - concrete pavement,
  - improved road roughness,
  - regular calibration,
- banned auto-calibration, a method where the calibration factors change according to statistically evaluated characteristic weights of traffic,
- improved data quality checks which included daily checking of data.

Today, most WIM systems have built-in temperature and (potentially) velocity calibration algorithms as well as quality checks that ensure that results are stable and of expected quality. In addition, the data owners, when importing data from the systems into the traffic databases, perform a number of their own data quality validations to eliminate the unreliable information.

2.2 WIM information for different countries

This section contains information on the WIM situation for the CEDR funding and partners countries (Slovenia, Ireland, UK, Netherland, France, Denmark, Germany) and aims to address the following issues:

- **Basic information:** Do the countries have a WIM program? For how long have they collected WIM data? Who is operating the WIM program?
- **WIM sites:** The number of permanent/portable WIM sites; type of road and number of lanes that WIM system is collecting data on; criteria for WIM site selection.
- **WIM technology:** What WIM technologies are used? How the systems are calibrated/recalibrated? What is the experienced reliability of the systems?
- **WIM data:** The types of traffic data (axle loads, gross vehicle weight, number of axles etc.); photographs of vehicle; availability of cars/light vehicle information, maximum number of recorded axles, time stamp precision; format of WIM data for archiving; quantity of data; accuracy of data; quality of data.
- **WIM data applications:** Which applications the WIM data is used for?

2.2.1 Slovenia

Slovenia has a well-developed WIM program. Data has been collected for the last 15 years for a number of applications, including bridge assessment.

WIM sites

WIM data is collected on the entire national road network. Portable bridge WIM systems are used to collect 1-week to 1-month data samples at 95 locations. In addition, 18 long-term (permanent) locations are being installed on the motorways. Figure 10 shows the 40 periodic portable locations on the national road network that are repeated every year.

In addition to these periodic sites which have been collecting data for over 10 years, there are annually:

- approximately 55 sites that are selected on a yearly basis; these measurements are typically 1-week long,
- up to ten sites installed specifically for safety assessment of bridges,
- a few sites to control dangerous goods.

Typical installations cover 4 lanes on the motorways (2 in each direction) or both lanes on the bidirectional national roads.

There are practically no criteria used for WIM site selection in Slovenia. This factor sometimes leads to lower accuracy of the data and requires considerable knowledge and expertise concerning bridges to obtain acceptable accuracy. In the case of appropriate bridges, with smooth pavement and spans from 10 to 20 m bridges, high accuracy of the WIM data can be expected.

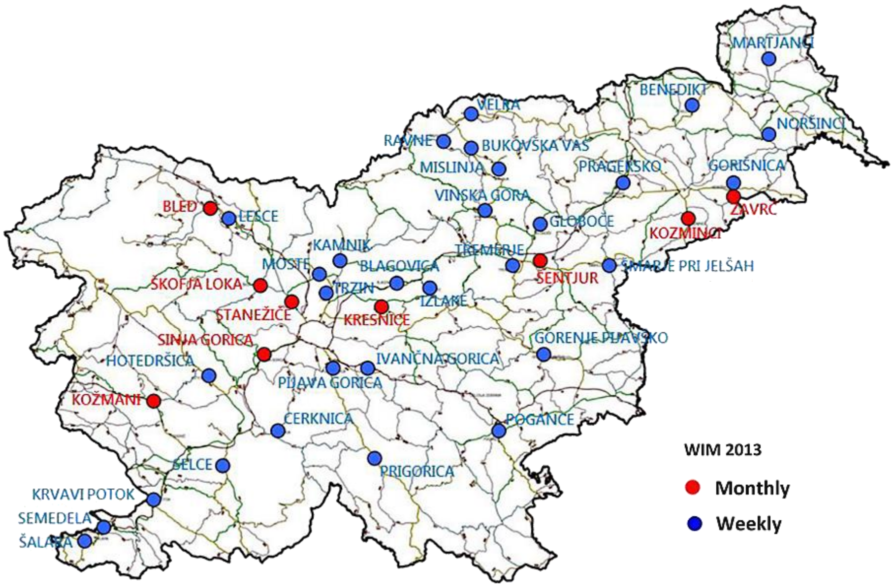


Figure 10: Locations of periodic WIM sites in Slovenia

WIM technology

A bridge weigh-in-motion system (called SiWIM®), developed in Slovenia (Žnidarič, Lavrič, & Kalin, 2010), is used. ZAG developed the first version of a SiWIM® system prototype in 1997 within the WAVE project (2001). Subsequently, in cooperation with the Cestel Company, SiWIM® has been considerably improved. Today, the third generation of the SiWIM® system is in use. Major improvements with respect to reliability and accuracy of results were achieved during the recent FP7 Bridgemon project (Corbally, et al., 2014).

Figure 11 shows typical bridge-WIM instrumentation with strain transducers on a beam-and-slab and a slab bridge in Slovenia.

For the calibration of the SiWIM® system, COST 323 (2002) rules are used. Each site is calibrated with one or two pre-weighed vehicles that are run over the bridge at least 10 times in each direction, with two different velocities. No recalibration is needed for the short-term measurements on the national roads. For the permanent measurements on the motorways that are intended primarily for pre-selection of overloaded vehicles, recalibrations are done at any time, based on the free traffic flow vehicles that are checked on the static scales. Calibration and recalibration are performed by the contractor performing the measurements.

Figure 11: Typical SiWIM® installations in Slovenia

WIM data

WIM data is available in vehicle-by-vehicle format, Figure 12, with time stamp precision of less than 0.002 s, stored in a text file where each line describes a vehicle record with the following information:

- time,
- velocity,
- vehicle category,
- number of axles,
- axle configurations,
- gross weight,
- axle loads,
- length of vehicle,
- axle spacings,
- temperature,
- error and warning codes,
- ESAL (Equivalent Single Axle Load) value for the vehicle, etc.
- quality estimator.

There are no restrictions in the system for maximum number of axles that can be recorded for individual vehicles. The system allows weighing of cars and light vehicle, but this data is usually not collected.

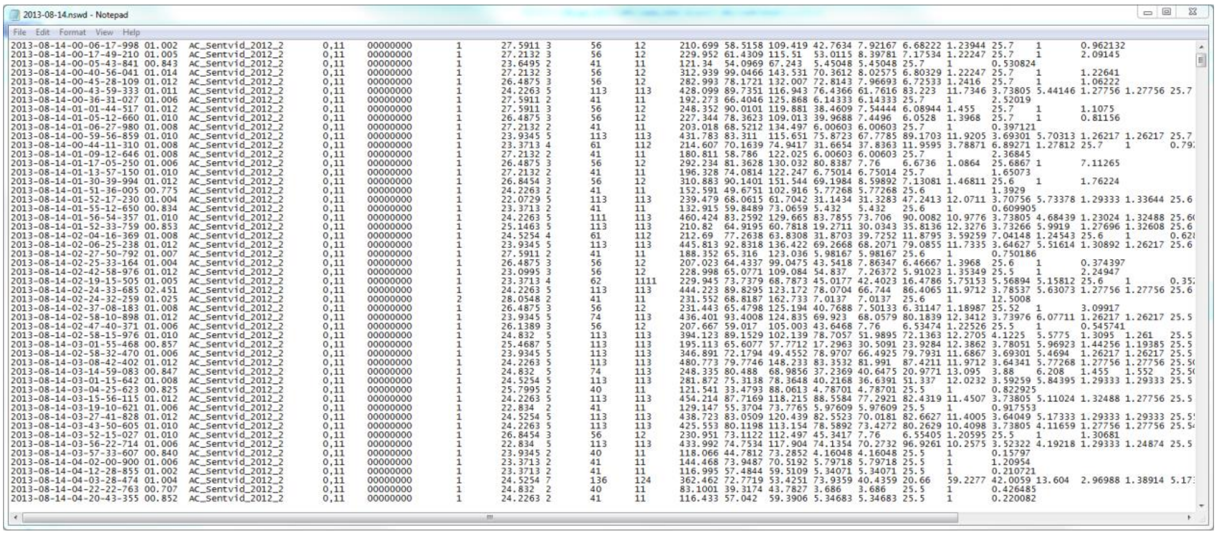


Figure 12: Example of Slovenian vehicle-by-vehicle file

In addition to information and photographs for each vehicle, SiWIM® provides some unique structural information that optimises structural analysis of the bridge:

- influence lines of the bridge,
- load distribution factors,
- dynamic amplification factor.

To evaluate this information, some specific knowledge is required.

The quantity of WIM data depends on the duration of WIM measurement at the selected site. For a limited number of permanent sites, a few years of WIM data is available, whereas for portable locations, various numbers of periodic weekly or monthly data exist.

The Accuracy of WIM is calculated according to the European specifications for weigh-in-motion (COST 323, 2002). Typically, Class C(15) is achieved, which means that for a confidence interval of typically 95%, the errors are within ±15% for gross vehicle masses, ±18% for axle group loads and ±20% for single axle loads. On better sites with smooth pavement class B+(7) can be attained.

The Quality of WIM data is partially controlled automatically (temperature and velocity calibration as well as reconstruction of missed axles). Data quality checks to eliminate unreliable information are currently performed manually. More comprehensive data quality post-processing algorithms are currently under development (see Section 3.2).

WIM data application

In Slovenia, WIM data is used for the following application:

- traffic studies,
- pavement design and reconstruction,
- bridge assessments,
- pre-selection of overloaded vehicles,
- tracking dangerous goods,
- research and development.

In relation to bridge applications, traffic load modelling and development of rating/assessment loading schemes within the bridge safety assessment procedures are the most important aspects of using WIM data (See Sections 0 and 4.3).

2.2.2 Ireland

WIM sites

There are 6 WIM sites in The Republic of Ireland. These sites have only been recently installed and have been collecting accurate WIM data since the start of 2014. Previous to this, only traffic count data was available and no information was available on vehicle weights. These sites are located on routes leading to and from Dublin, Ireland's capital city. The locations of the sites are shown in Figure 13.

The sites are situated mostly on primary roads with two lanes in each direction. The lane configuration of the sites are summarised in Table 1. For all sites, WIM sensors are installed in all lanes in each direction. Although some efforts were made to select suitable WIM sites based on the recommendations in COST 323 (2002), the location of existing power supplies was a deciding factor for the location of these sites. This has had a negative impact on accuracy in some cases.

Table 1: Road type and lane configuration of Irish WIM sites

Site	Road Type	Lane Configuration
M1	Primary – Motorway	2 + 2
R147	Regional – Previously a primary route (N3). M3 motorway has now replaced this route.	2 + 2 (incl. Bus lane in each direction)
M4	Primary – Motorway	2 + 2
M7	Primary – Motorway	2 + 2
M11	Primary – Motorway	2 + 2
N7	Primary – Dual Carriageway	3 + 3

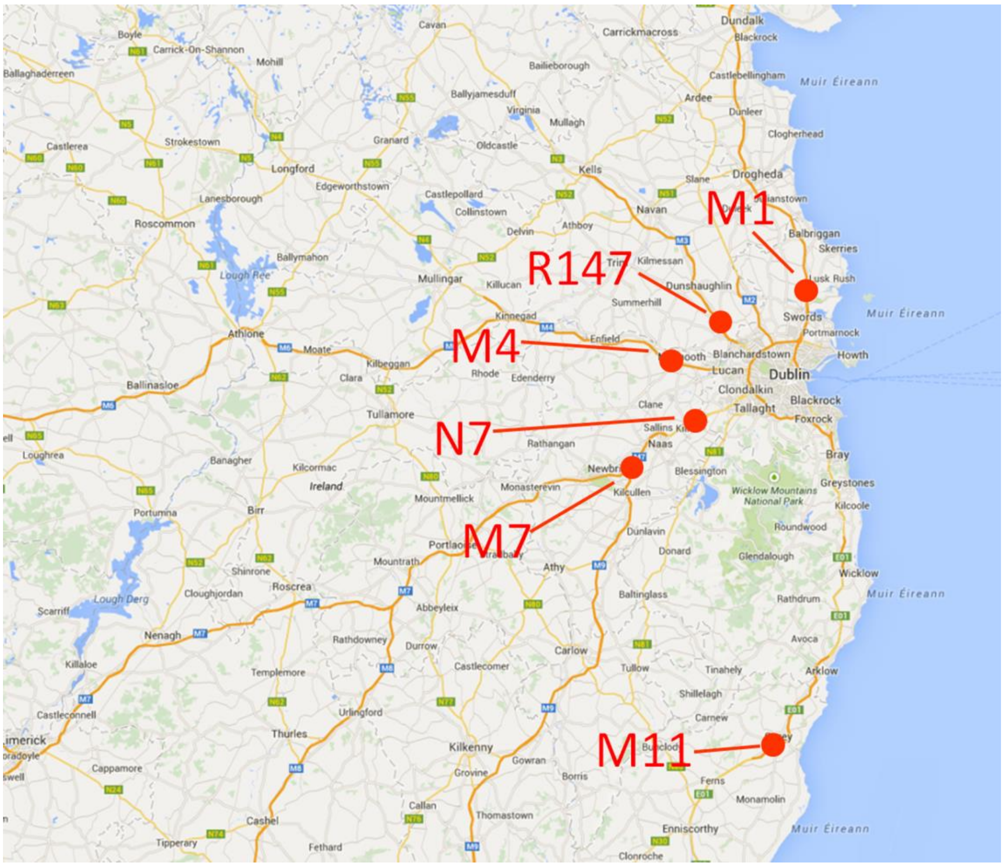


Figure 13: Location of Irish WIM sites in Greater Dublin Area.

WIM technology

Two piezo-polymer WIM sensors and one induction loop are installed in the road surface in each lane. The WIM sensors were supplied by TDC Systems Ltd. The data is recorded by HI-TRAC traffic management units (TMUs). A typical layout of the WIM system and the installation is shown in Figure 14.

The COST 323 accuracy classification scheme is used to determine the accuracy of the systems. Test Plan No. 1.2, as described by COST 323, is used to determine the accuracy class for each lane. This involves 15 runs with a fully loaded truck and 15 runs with a half loaded truck. This process is repeated every six months to recalibrate the systems and determine the accuracy class.

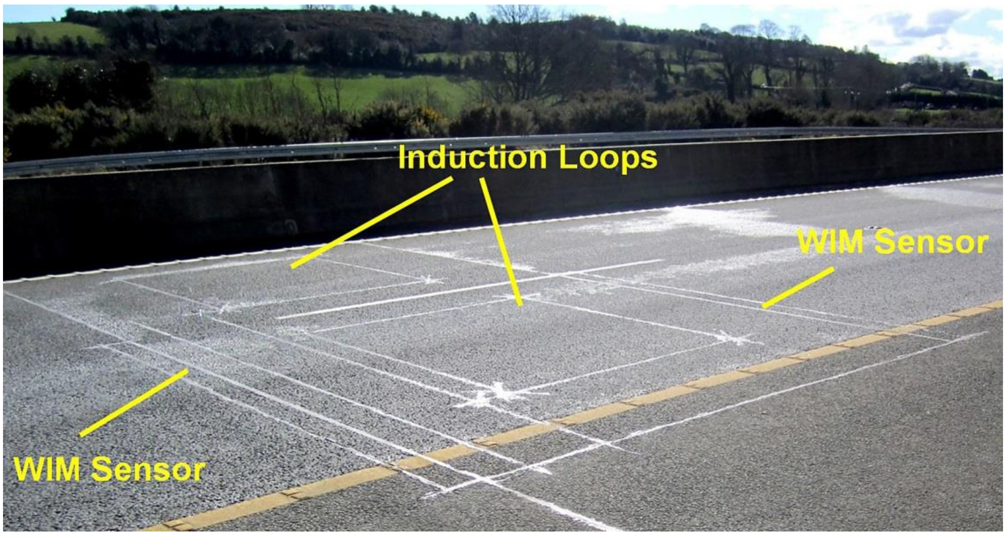


Figure 14: Layout of WIM System (M11 site).

WIM data

The data is stored on a server and vehicle-by-vehicle records can be outputted in .csv format. The following information is recorded for all vehicles (including cars) that pass over the WIM system:

- site ID,
- date and time stamp to the nearest 0.01 second,
- lane,
- direction,
- vehicle class,
- length,
- headway,
- gap,
- speed,
- gross vehicle weight,
- error flags,
- number of axles (note: there is no maximum number of axles that can be recorded),
- axle weights,
- axle spacings.

Cameras are installed at most of the sites to capture overview images of heavy trucks. Due to the required storage, images for all vehicles are not recorded. Images are stored if the vehicle meets one of the following criteria:

- gross vehicle weight greater than 50 tonnes,
- has a single axle greater than 16 tonnes,
- has a tandem greater than 28 tonnes,
- has a tridem greater than 34 tonnes.

Examples of vehicle overview images are shown in Figure 15. These cameras capture images at all times of the day but night-time images are usually not usable.

(i) 9-axle, 137 t truck at M11 site

(ii) 9-axle, 130 t truck at M1 site

Figure 15: Overview images of some heavy trucks weighed at Irish WIM sites.

It is aimed to achieve a COST 323 accuracy class of C(15) at all sites. This C(15) target accuracy is achieved for most lanes. The sites where C(15) was not achieved, appear to be affected by poor pavement profile and degradation of pavement. However, on other lanes with very good pavement quality, it has been possible to achieve class B+(7).

Temperature variation affects the accuracy of the WIM sensors and is compensated for using temperature adjustment curves within the WIM system. These curves can be manually updated or set to auto update. It has been found that correct temperature compensation is critical for maintaining accurate WIM measurements.

The systems are recalibrated every 6 months. Between calibrations the data recorded by the systems is monitored for loss of calibration or calibration drift. These properties are monitored on a quarterly basis by examining statistics which are plotted as part of a WIM quarterly report which mostly examines general weight statistics for reporting to senior management. The mean daily/weekly steer axle weight on five-axle trucks and the mean weekly gross weight – see Section 3.2 – are monitored to detect loss of weight calibration. Additionally, the rearmost axle spacing on five-axle trucks is examined to ensure axle spacings are being measured correctly. Screen shots of some of these plots are taken from the quarterly reports and are shown in Figure 16 and Figure 17. These plots show a site with no calibration issues. The steer axle weight in Figure 16 remains at a constant level of about 6 t and the peak in the axle spacing histogram in Figure 17 is at 1.3 – 1.4 m which suggests that no drift or loss of calibration has occurred.

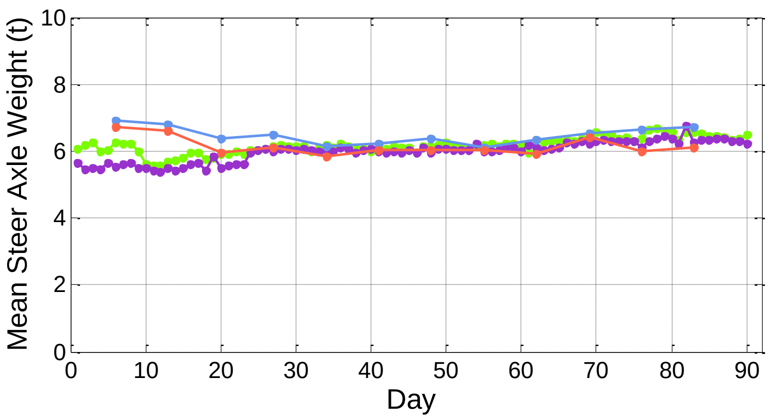


Figure 16: Mean steer axle weight on five-axle trucks.

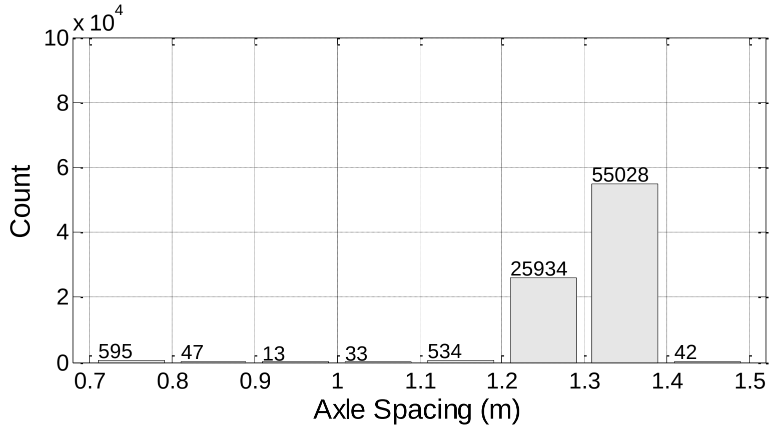


Figure 17: Rearmost axle spacing on five-axle trucks.

2.2.3 UK

WIM sites

The Department for Transport, the government department responsible for the transport network in England (but not the other regions of the UK), had approximately 29 WIM sites which were recording information since 1995 but have recently ceased operating these sites. A site corresponds to one direction at each location. If both directions are recorded it is counted as two sites. Details of 12 sites (6 locations) were obtained and are shown in Figure 18 and Table 2. Each site has data recorded in both directions.

It should be noted that although the Department for Transport have ceased collecting WIM data, the Driver and Vehicle Standards Agency are collecting WIM data at 12 sites in the UK. Their WIM systems are linked with Automatic Number Plate Recognition (ANPR) and overview images which are used for targeting enforcement activities. These sites have been installed over the past seven years. Full vehicle-by-vehicle data is not recorded at these sites but GVW, length and speed is recorded for every vehicle (including cars) with a successful ANPR read. Overweight vehicles which are identified at these WIM sites may be subsequently stopped and weighed on a weigh bridge. These weight measurements are used for quality assurance purposes to monitor calibration on the WIM systems. These Driver and Vehicle Standards Agency WIM sites will not be discussed further here and all subsequent information presented here refers to the Department for Transport sites.

WIM technology

Piezo polymer WIM sensors were the dominant technology and the systems were recalibrated twice per year.

Figure 18: Locations of six of the Department for Transport WIM sites in England.

Table 2: Road type and lane configuration of six of the Department for Transport WIM sites

Site	Road Type	No. Lanes at Site	Lanes With WIM
M4	Motorway	3 + 3	3 + 3
M6	Motorway	3 + 3	2 + 3
M6	Motorway	3 + 3	2 + 3
M20	Motorway	3 + 3	3 + 3
M1	Motorway	3 + 3	3 + 3
A14	Dual Carriageway	3 + 3	3 + 3

WIM data

The following information was recorded for all vehicles (including cars) that passed over the WIM system:

- site ID,
- date and time stamp to the nearest second,
- lane,
- vehicle class,
- length,
- headway,
- gap,
- speed,
- gross vehicle weight,

- wheelbase,
- number of axles (note: a maximum of 10 can be recorded),
- axle weights,
- axle spacings.

The accuracy of the systems has a mean measured to static ratio of +/- 0.1 and a coefficient of variation less than 18%. There are no quality assurance checks such as those described for Ireland in Chapter 2.2.3. No truck images are recorded at these sites.

2.2.4 Netherlands

WIM sites

In the late 1990s, the Netherlands developed the WIM+VID (video) system which weighs and captures images of vehicles. This system was reviewed in a US Federal Highway Administration report (FHWA 2007) and this report was used to obtain much of the information on the Netherlands WIM in this chapter. In 2006, when the study was performed, there were six WIM+VID sites operating in the Netherlands (there is a site for each direction at three locations). These sites are on the major roads leading to and from the Port of Rotterdam. By 2011, another two WIM+VID sits had been added on another road leading to the Port of Rotterdam and as part of a separate project, a multi-sensor WIM system had been installed near Arnhem to test the accuracy of the sensors (van Loo & Jacob 2011). This test was finalized, and based on the outcome a strategy to use WIM data in enforcement on overloading was created. This was the basis for a new investment in Weigh In motion systems in 2010. The WIM sites are typically located on a 3+3 lane motorways with WIM installed on the two slower lanes in each direction. It is believed that there are now a total of 20 WIM sites– see Figure 19. In the Netherlands, a site corresponds to one direction at each location.

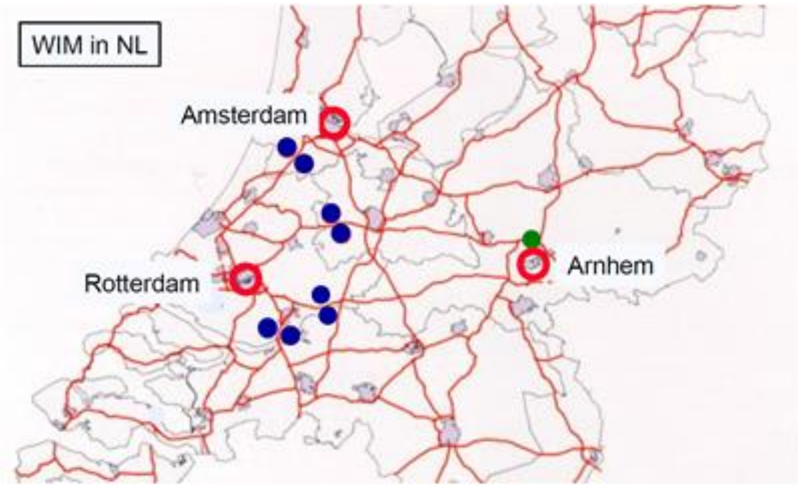


Figure 19: Locations of WIM sites in the Netherlands.

WIM technology

The WIM+VID sites consist of two rows of Kistler Lineas piezo-quartz sensors and two induction loops per lane. There are also cameras to capture overview images and licence plate images. Night-time images are also captured by the cameras but the trucks are not always visible. The layout of the sites is shown in Figure 20 and an example of the vehicle images recorded is given in Figure 21.

Figure 20: Layout of a Dutch WIM site (from van Loo & Jacob 2011).

Figure 21: Example of a heavy vehicle images recorded at a Dutch WIM site.

WIM data

The following information is recorded for all vehicles (including cars) in the Netherlands that pass over the WIM sensors:

- vehicle ID,
- direction,
- lane,
- date and time stamp to the nearest 0.01 second,
- class,
- front license plate,
- rear license plate,

- distance to previous vehicle,
- road temperature,
- bumper to bumper length,
- speed,
- gross vehicle weight,
- number of axles (note: a maximum of 10 can be recorded),
- axle weights,
- axle spacings.

As the systems are used for pre-selection for static weighing, trucks which have passed over the WIM sensors may be statically weighed subsequently. Every time static weighing is performed, the results are compared with the WIM measurements and an accuracy report is produced and the results are used to recalibrate the system, if required. This typically occurs on a weekly or monthly basis. As a results, the accuracy of the axle weight measurements is usually within ±15% for 95% of axles measured (FHWA 2007).

WIM data application

The WIM data gathered in the Netherlands is used for:

- Determining pavement loading for design and maintenance.
- Pre-selection of overloaded trucks for static weighing.
- Identifying companies which are the worst offenders for overloading.
- Monitoring special transports.

2.2.5 France

WIM sites

There are 29 WIM sites in France, Figure 22. In total, 48 lanes are monitored. These WIM stations have been installed at strategic places to monitor traffic on roads with high volume of trucks, at borders of the country, near harbors, etc.

This network is called “réseau de présélection de surcharges”, thus they are aimed at preselection, and not direct enforcement. Indeed, these stations are used by the regional centers of the ministry of Ecology (called Directions Régionales de l’Environnement, de l'Aménagement et du Logement, DREAL) in order to preselect vehicles that will be weighed on static scales during control operations on roads or in companies.

WIM technology

The systems are installed by the company Sterela. A camera is included in order to take a picture and detect the license plate number of the truck. The dimensions and weights of the truck are detected and compared against the national regulation limits. An alert for not abiding the regulation is given instantly. A screenshot of the software of the system is shown in Figure 23, with a vehicle that has the second axle overloaded (above the limit of 13 tons):

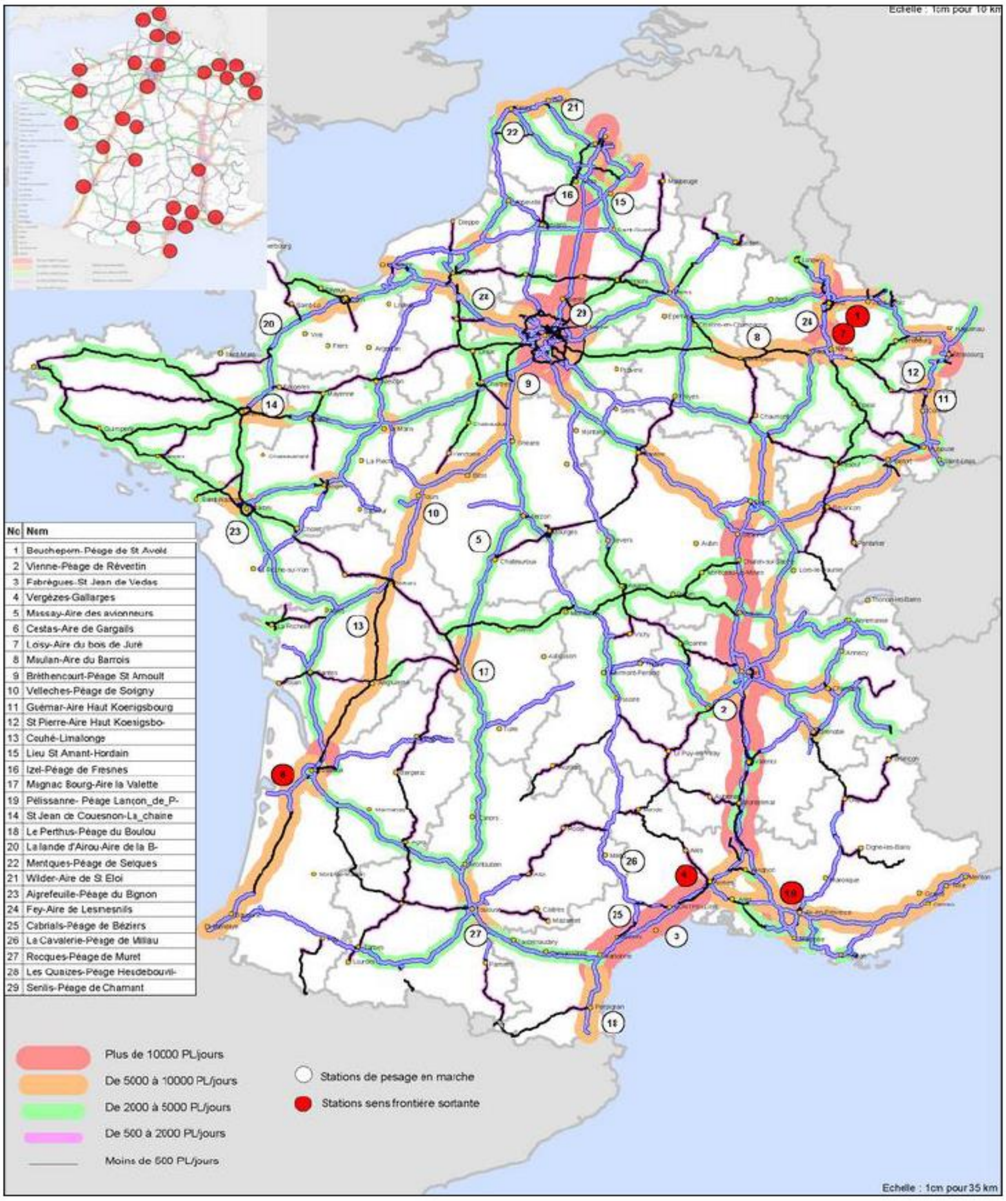


Figure 22: French WIM sites

WIM data

The measured data is the following:

- Hourly flow off all vehicles,
- Hourly flow of overweight vehicles,
- Individual data on trucks (GVW>3.5t): timestamp, weight per axle, GVW, speed, distances between axles, distance between bumper and first axle. A photography is taken by the camera if there is a violation of the regulation.
- In a specific file are stored aggregated data on flow, speed, load, length for the 22 categories of vehicles. In this file, the damage done to the road by each category of vehicle is calculated.

The stations are automatically calibrated with accuracies as follows:

- GVW: ±10%, COST 323 class B(10),
- weight per axle: ±15%,
- speed: ±1%,
- total length of vehicles: ±10%,
- distances between axles: ±1%,
- recognizing of the license plate number: ±80%.

The total length of the vehicles is less certain as the measurement of the distance from the front bumper to the first axle is done by electromagnetic loop, and thus is less accurate.

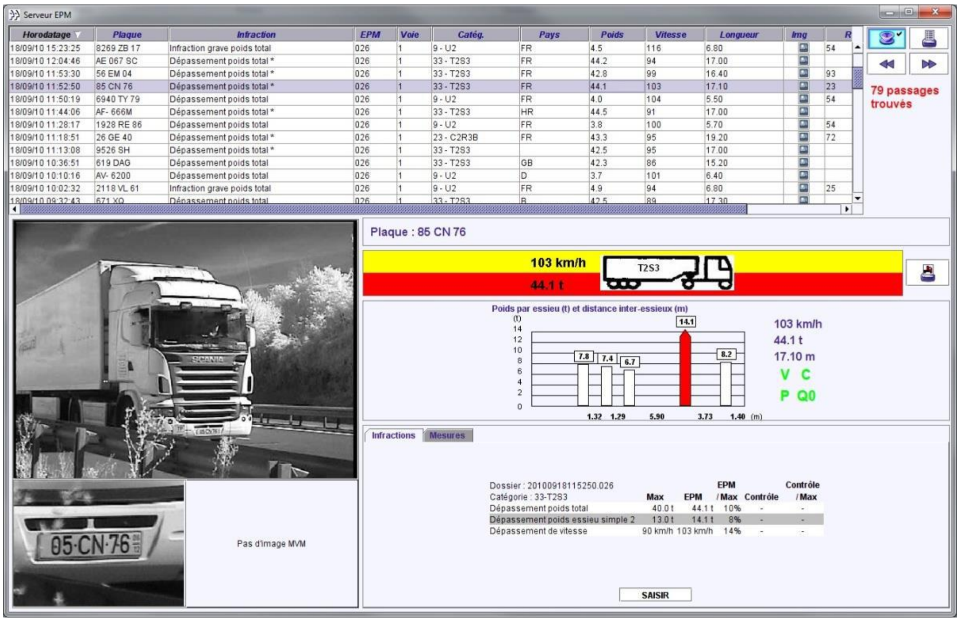


Figure 23: French WIM data monitoring software

WIM data application

The WIM data is primarily used for monitoring of the traffic flows of the various roads and, according to specific requests, for scientific and technical purposes (research and studies).

2.2.6 Denmark

In Denmark, the Danish Road Directorate (DRD) currently operates 8 permanent WIM sites, while the 9th is being installed in 2015. All sites are operated by the Department of Traffic Statistic at DRD (DTS/DRD).

WIM data has been widely used in Denmark for more than 15 years, and provides an important source of information regarding traffic statistics. Among other sources for collecting information on the traffic flow, the DTS operates approx. 60 sites with induction loops for "pattern recognition" of vehicles, approx. 400 sites where traffic is counted and length is recorded, and an even larger number of sites with counting only.

WIM sites

As per January 1st 2015, DTS operates a total of 8 permanent WIM sites which are located as shown in Figure 24.

The sites are situated mostly on primary roads but minor regional and urban roads are also represented. The type of road and lane configuration of the sites are summarised in Table 3.

WIM technology

All sites are equipped with Kistler Lineas piezo-quartz sensors, typically with two sensors per lane. Furthermore, each lane has a corresponding induction loop installed in the road surface to classify the passing vehicles (except the Åbenrå site). Data from all lanes and inductions loops are recorded and stored in separate modules at the sites. Data can be transferred automatically to DRD for further processing.

Figure 24: Locations of WIM sites in Denmark

Table 3: Road type and lane configuration of WIM equipment at Danish WIM sites

Site	Road Type	Lane Configuration
Støvring	Primary, motorway	2 + 2 (total)
Fårvang	Regional, highway	1 + 1 (total)
Brande	Primary, motorway	2 + 2 (total)
Åbenrå	City, urban road	1 + 1 (total)
Farum	Primary, motorway (test site, not standard equipment)	1 + 0 (partial WIM coverage, road is 2+2)
Solrød	Regional, highway.	1 + 1 (total)
Fjenneslev	Primary, motorway.	2 + 2 (total)
Bårse	Primary, motorway.	1 + 0 (partial, road is 2+2)

Since most WIM sites have been operational for more than 10 years, the equipment has been upgraded gradually. Historic data is (to a certain extent) stored and is accessible, but due to the change and general update of the software and the storage systems, some historic data before 2008 cannot be accessed.

WIM data

WIM data is stored in a vehicle-by-vehicle format (Figure 25) with a time stamp precision of only 1.0 sec The systems would be capable of producing time stamps with a precision equal to 0.01 s or better if the software is upgraded (not free of charge). Files are stored as plain text files where each line describes a vehicles record with the following information:

- date and time (to the nearest full second),
- lane,
- speed,
- length,
- class,
- gap (distance between 2 successive vehicles),
- check of direction,
- number of axles,
- gross weight,
- vehicle class,
- axle load, left,
- axle load, right,
- axle distance,
- the above 3 values to be repeated for up to 9 axles.

As described earlier, induction loops are installed in each lane. There are no camera recordings or photographs.

The quality and reliability of the recorded WIM data is considered good in general. Calibration is carried out at approximately 15-18 months intervals. Typical change of the calibration factors per site is in the order of 2-3%. Calibration is focused on achieving max accuracy for heavy axles. Calibration is not carried out according to the rules set out by COST 323.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	* BEGIN																
2	* FORMAT = TDSVBVWIM																
3	* GENERATOR = ATKI tdsdatavbv.php 1.0																
4	* SITE = 35030881																
5	* STARTREC = 00:00 14/11/22																
6	* STOPREC = 24:00 14/11/22																
7	* DATEFORM = YY/MM/DD																
8	* CHANNELS = 1 2																
9	* UNITS = Metric																
10	* PRUNITS = KPH-CM-KG																
11	* HEAD = datetime	lane	speed	length	class	gap	wrong_di	axels	weight	sclass	axel0l	axel0r	axeldist01	axel1l	axel1r	axeldist12	axel2l
12	22-11-14 00:01:02	1	88	1370	9	65535	0	3	20685	0	3135	3050	624	4987	4003	134	28
13	22-11-14 00:01:44	1	112	450	2	41300	0	2	1740	1	534	482	276	392	332	0	
14	22-11-14 00:01:49	1	124	450	2	4950	0	2	1712	1	510	506	267	324	370	0	
15	22-11-14 00:03:36	1	126	420	2	65535	0	2	1354	1	403	407	249	269	274	0	
16	22-11-14 00:05:04	1	97	600	4	65535	0	2	4256	4	902	762	321	1353	1238	0	
17	22-11-14 00:05:12	1	104	340	2	7390	0	2	1413	1	406	409	224	297	299	0	
18	22-11-14 00:05:18	1	95	340	2	5370	0	2	984	1	324	280	232	193	186	0	
19	22-11-14 00:07:09	1	149	400	2	65535	0	2	1524	1	398	371	257	401	353	0	
20	22-11-14 00:09:19	1	86	1640	9	65535	0	5	44876	98	3829	3903	354	6456	6520	570	35.
21	22-11-14 00:10:44	1	119	410	2	65535	0	2	1399	1	401	369	248	322	306	0	
22	22-11-14 00:11:32	1	134	440	2	47860	0	2	1890	1	572	521	276	374	422	0	
23	22-11-14 00:12:20	1	107	360	2	47170	0	2	1341	1	376	400	234	293	269	0	

Figure 25: Example of Danish vehicle-by-vehicle file (imported directly into Excel).

Quality assurance checks are carried out on both a weekly and monthly basis, where data is monitored for loss of calibration and/or calibration drift. If irregularities are observed then corrective actions are initiated.

WIM data application

The Danish WIM data is operated by the Department of Traffic Statistics at DRD, whereby the main focus has been on issues such as:

- traffic intensity, traffic characteristic, traffic flow and related issues,
- general road safety,
- illegal overloading (co-operation with Danish Police Authority),
- speed,
- calculation of traffic loading in the form of Equivalent Single Axle Loads for pavement design, maintenance and assessment.

At the time of writing (March 2015), the Danish WIM data is not used actively in relation to bridge loading. However, the Danish WIM data was used for the preparation of the report Reliability-Based Classification of the Load Carrying Capacity of Existing Bridges (DRD, 2004).

2.2.7 Germany

WIM sites

There are 14 WIM sites in Germany which currently deliver data. The sites are situated only on federal highways. A typical WIM installation covers only slow lanes (12 sites), whereas for the other 2 sites, slow and next-to-slow lane are instrumented, Table. For most sites, WIM data are collected in both directions.

WIM technology

Piezo-quartz (Kistler Lineas) WIM technology is used. The system is calibrated according to COST 323 rules (2012). An accuracy B+(7), at least B(10), has to be achieved (Tetzner, 2011). The system is recalibrated up to 2 times per year.

Table 4: Number of WIM sites on federal highways in Germany

Site	Number of sites
Slow lane only	12
Slow lane and next to slow lane	2
Three or more lanes	/

WIM data

WIM data is available in vehicle-by-vehicle format with time stamp precision of nearest 0.01 seconds or less with the following information (Tetzner, 2011):

- all individual axle loads of a vehicle,
- axle spacing to each other,
- speed of a vehicle,
- vehicle length,

- distance between vehicle and vehicle travelling ahead,
- time of measurements,
- total weight of the vehicle,
- possible total overload,
- type of the axle assembly,
- possible overloading of singe axles or axle assemblies,
- vehicle type.

There are no restrictions in the system for maximum number of axles that can be recorded for individual vehicles. The system does not record the cars and light vehicle weights and there are no photographs of the measured trucks.

The accuracy of axle loads has been measured and amounts to ±10%. Plausibility checks are performed on the recorded data.

WIM data application

The main objectives of the WIM data collection in German are (Tetzner, 2011):

- improved efficiency in the construction and maintenance of roads, bridges and engineering structures,
- increased traffic safety,
- further development of the efficiency in road use,
- preselection of overloaded vehicles.

2.3 Summary results of WIM system information in each country

Summary results on the weigh-in-motion situation in the funding and partners countries reveal that all of them collect WIM data but not all use it for bridge applications.

Table 5 shows that WIM data is mostly collected on the primary roads (motorways and carriageways). As a rule, long-term (permanent) installations are used and provide large amount of WIM data. In Slovenia, most WIM systems are portable and collect 1-week to 1-month data samples. About 50% of locations are reinstalled each year for the last 10 years.

A typical WIM installation covers all lanes with heavy duty vehicles in each direction, therefore the number of WIM locations is equal to number of WIM sites. The exception is the UK and the Netherlands, where a site corresponds to one direction at each location, i.e. both directions represent two sites. In Germany, typically slow lanes in both directions are instrumented. The Criteria used for WIM site selection in these countries are not uniform though some efforts to select proper WIM sites based on (COST 323, 2002) were made in Ireland.

The information about WIM technologies is summarised in Table 6. Pavement WIM systems (section 2.1.1) are used in most countries, only Slovenia is using a bridge WIM system. Some countries (Ireland, Slovenia, France, Germany) use COST 323 rules to calibrate the systems, whereas recalibration is mostly based on free flow vehicles that are checked on the static scales. Number of recalibrations per year depends on a given country. The accuracy of the system in Ireland, Slovenia, France and Germany is calculated according to the COST 323 specifications. Typically, class C(15) is achieved in Slovenia and Ireland and B(10) in France and Germany. In the UK, the accuracy of the systems has a mean measured to static ratio of +/- 0.1 and a COV less than 18%. In the Netherlands, the axle weight measurements are usually within ±15% for 95% of axles measured.

Table 5: Summary results on WIM sites information in each country

	Number of WIM sites	WIM data since	Type of roads + lane configuration	Instrumented lanes per site
Slovenia	110	2001	Regional (1+1) Motorways (2+2)	All lanes in each direction
Ireland	6	2014[(2)]	Regional (2+2) Motorways (2+2) Dual Carriageway (3+3)	All lanes in each direction
UK[(1)]	29	1995	Motorways (3+3) Dual Carriageway (3+3)	Mostly, all lanes in one direction[(3)]
Netherlands	20	2006	Motorways (3+3)	Typically, two slower lanes in one direction[(3)]
France	29	Late 1980s	Motorways (2+2)	Mostly, all lanes in each direction
Denmark	8	2000	Motorways (2+2) Regional (1+1) City, urban road (1+1)	Mostly, all lanes in each direction
Germany	14	n.a.	Federal highways	Typically, slow lane in both direction

(1) The sites examined were operated by the Department for Transport which is only responsible for the transport network in England but not the other regions of the UK;

(2) Only traffic count data was available before;

(3) A site corresponds to one direction at each location. Both directions are recorded as two sites;

Table 6: Summary results on WIM system information in each country

	WIM technology	Type of sensors	Calibration; Recalibration	Accuracy of system
Slovenia	Bridge – WIM	strain gauges	COST 323 rules; Vehicles from free traffic flow[(1)]	COST 323; typically C(15) [(2)]
Ireland	Pavement - WIM	piezo-polymer	COST 323 rules; Every six months	COST 323; typically C(15) [(2)]
UK[(1)]	Pavement – WIM	piezo-polymer, piezo-quartz	From free traffic flow vehicle[(1)]; Twice per year	±0.1 mean, COV less than 18%
Netherlands	Pavement – WIM	piezo-quartz	From free traffic flow vehicle[(1)]; Weekly or monthly	Axle weight ±15% for 95% of data
France	Pavement – WIM	piezo-quartz, piezo-ceramic	COST 323 rules; Vehicles from free traffic flow[(1)]; Twice a year	COST323; B(10)
Denmark	Pavement – WIM	piezo-quartz	15-18 months interval	n.a.
Germany	Pavement - WIM	piezo-quartz	COST 323 rules; up to 2 times/year	COST 323; generally B(10)

(1) Recalibration is based on the free traffic flow vehicles that are checked on the static scales

(2) Slovenia and Ireland report accuracy up to B+(7) – ±7% for gross weight – on very smooth roads

Table 7 shows that WIM data in all countries is available in vehicle-by-vehicle format. This is typically stored in a file where each line describes a vehicle with at least the following information: time, speed, axle spacings, axle loads. In most countries, the information is recorded for all vehicles, including cars and light vehicle (if necessary). The maximum number of axles that can be recorded for an individual truck is not limited in Slovenia, Netherlands, Ireland and Germany, whereas in others countries, the limit is 9 or 10 axles. Typically the records contain additional information, such as vehicle category, axle configurations, gross weight, length of the vehicle, temperature, error codes, etc. Precision of the reported time stamp are appropriate (at least 0.1 s) in most cases, with exception of UK and Denmark (nearest second). Cameras are installed at sites in four of the countries (Slovenia, Ireland, Netherland and France) to capture images of the trucks, but the night-time images are not always visible. Quality of WIM data are controlled in almost all countries.

The WIM data in funding and partners countries are used for different purposes. Table 8 shows that Slovenia, UK, France and Germany use WIM data for bridge applications. Due to the proper format of WIM data, there is an opportunity to use it for bridge applications too in others countries. The exceptions are Denmark and UK, which should investigate whether it would be possible to store data in a more appropriate file format for bridge application (time stamp precision should be at least 0.01s). Chapter 4 describes the case studies from Ireland, France and Slovenia to demonstrate the importance of using WIM data with respect to bridge application.

Table 7: Summary results on WIM data information in each country

	Vehicle-by-vehicle format	Time stamp precision	Photographs of measured truck	Cars/light vehicles	Maximum number of axles	Any quality assurance checks
Slovenia	Yes	0.002 sec	Yes, but not on all sites	No, but it could be	No limit	Yes
Ireland	Yes	nearest 0.01 sec	Yes, but not for all vehicles	Yes	No limit	Yes
UK(1)	Yes	nearest second	No	Yes	10	No
Nether-lands	Yes	nearest 0.01 sec	Yes	Yes	No limit	Yes
France	Yes	0.01 sec	Yes	Yes	10	Yes
Denmark	Yes	1 sec(2)	No	Yes	9	Yes
Germany	Yes	nearest 0.01 sec or less	No	No	No limit	Yes

(1) At selected site only GVW, length and speed are recorded;

(2) The system is capable of producing time stamps with a precision equal to 0.01 s or better, but will require an (not free of charge) update of the software.

Table 8: Summary results on WIM data application in each partner country

	Bridge applications	Pavement applications	Traffic studies	Pre-selection
Slovenia	Yes	Yes	Yes	Yes
Ireland	No(1)	No(1)	Yes	No(1)
UK(1)	Yes(2,3)	Yes(2)	Yes(2)	Yes
Netherlands	Yes (in past)	Yes	Yes	Yes
France	Yes (exceptionally)	Yes (exceptionally)	Yes	Yes
Denmark	No(4)	Yes	Yes	Yes
Germany	Yes(5)	Yes(5)	Yes(5)	Yes(5)

(1) To date, the WIM data has only been used to review traffic loading, but there is potential to use data for other purposes.

(2) Source (Žnidarič A. , Heavy-Duty Vehicle Weight Restrictions in the EU - Enfrocement and Complience Technologies, 2015).

(3) For bridge protection, i.e. to stop the vehicles if the total weight exceeds the bridge capacity

(4) At the time of writing (March 2015), the Danish WIM data is not used actively in relation to bridge loading. However, in the preparation of Guideline Document 291 from 2004 “Reliability-Based Classification of the Load Carrying Capacity of Existing Bridges”,” the Danish WIM data was used.

(5) Source (Tetzner, 2011).

3 Guidelines for collecting and using WIM data

This chapter provides:

- an overview of existing guidelines for collecting WIM data (Section 3.1),
- a possible procedure for quality assurance of WIM data and for cleaning of erroneous data (Section 3.2),
- examples of good practice of using WIM data for bridge applications (Section 3.3) and
- a short summary of protocols recommended for using WIM data for bridge design (Section 3.4).

3.1 COST 323 guidelines for collecting WIM data

There is no official standard on weigh-in-motion in Europe. European WIM specification COST 323 (2002) provides a technical basis for an official standard. It gives general and detailed recommendations for site selection, installation, operation, calibration and assessment by testing of WIM systems. This chapter summarises the steps for collecting good WIM data based on COST 323. Only the basic information for each step is given, more details can be found in the relevant parts of the COST 323 report, as noted in brackets of each step title.

STEP 1. Choice of accuracy class with respect to the application (chapter 4)

The WIM systems are classified in six accuracy classes, Table 9, which are defined by the confidence interval of the relative errors (δ in %) with respect to the static loads or weights. Each of them corresponds to a range of applications and requirements:

- **Statistics**: δ up to 30% (classes D+(20) or D(25)); economical and technical studies of freight transport, general traffic evaluation on roads and bridges, collecting statistical data, etc.
- **Infrastructure and preselection**: δ up to 20% (classes B(10) or C(15)); detailed analysis of traffic, design and maintenance of roads and bridges, accurate classification of vehicles, preselection for enforcement, etc.
- **Legal purposes**: δ up to 10% (classes A(5) or B+(7)); enforcement and industrial applications, but only if the legislation allows the use of WIM for that purpose.

For different purposes in the case of bridge application, classes B(10), C(15) or D+(20) can be used.

STEP 2. Choice of WIM sites (chapters 5 and I-2)

The specification defines three classes of WIM site based on road geometry and pavement characteristics as presented in Tables 9 and 10. An indication as to the accuracy class that is likely to be achieved at a site of a given class is then given in Table 12. The particular requirements for bridges are summarised in Table 13. It should be noted that this table differentiates slightly from the original one from the COST 323 specifications as the appropriate span lengths and bridge types were updated according to the most recent practise and knowledge (Corbally, et al., 2014).

Table 9: Tolerances of the accuracy classes (δ in %)

Criteria (type of measurement)	Domain of use	Accuracy Classes: Confidence interval width δ (%)						
		A (5)	B+ (7)	B (10)	C (15)	D+(20)	D (25)	E
1. gross weight	> 3.5 t	5	7	10	15	20	25	> 25
axle load	> 1 t							
2. group of axles		7	10	13	18	23	28	> 28
3. single axle		8	11	15	20	25	30	> 30
4. axle of a group		10	14	20	25	30	35	> 35

Table 10: Classification and criteria of WIM sites – pavement characteristics

			WIM Site Class		
			I (Excellent)	II (Good)	III (Acceptable)
Rutting (3 m – beam)		Rut depth max. (mm)	≤ 4	≤ 7	≤ 10
Deflection (quasi-static) (130 kN - axle)	Semi-rigid Pavements	Mean deflection (10^{-2} mm) Left/Right difference (10^{-2} mm)	≤ 15 ± 3	≤ 20 ± 5	≤ 30 ± 10
	All bitumen Pavements	Mean deflection (10^{-2} mm) Left/Right difference (10^{-2} mm)	≤ 20 ± 4	≤ 35 ± 8	≤ 50 ± 12
	Flexible Pavements	Mean deflection (10^{-2} mm) Left/Right difference (10^{-2} mm)	≤ 30 ± 7	≤ 50 ± 10	≤ 75 ± 15
Deflection (dynamic) (50 kN - load)	Semi-rigid Pavements	Deflection (10^{-2} mm) Left/Right difference (10^{-2} mm)	≤ 10 ± 2	≤ 15 ± 4	≤ 20 ± 7
	All bitumen Pavements	Mean deflection (10^{-2} mm) Left/Right difference (10^{-2} mm)	≤ 15 ± 3	≤ 25 ± 6	≤ 35 ± 9
	Flexible Pavements	Mean Deflection (10^{-2} mm) Left/Right difference (10^{-2} mm)	≤ 20 ± 5	≤ 35 ± 7	≤ 55 ± 10
Evenness	IRI index	Index (m/km)	0 - 1.3	1.3 - 2.6	2.6 - 4
	APL	Rating (SW, MW, LW)	9 – 10	7 - 8	5 - 6

Table 11: Classification and criteria of WIM sites – road geometry

	WIM Site Class		
	I (Excellent)	II (Good)	III (Acceptable)
Longitudinal slope	< 1 %	< 2 %	< 2 %
Transverse slope	< 3 %	< 3 %	< 3 %
Radius of curvature	>1000 m	>1000 m	>1000 m

Table 12: WIM Accuracy Class Likely to be Achievable in given WIM Site Class

Accuracy Class	WIM Site Class		
	I (Excellent)	II (Good)	III (Acceptable)
A(5)	Sufficient	Insufficient	Insufficient
B+(7)	Sufficient	May be Sufficient	Insufficient
B(10)	Sufficient	Sufficient	Insufficient
C(15)	More than Sufficient	Sufficient	Sufficient
D+(20) - D(25)	More than Sufficient	More than Sufficient	Sufficient

Table 13: Bridge selection criteria

Criteria	Optimal	Acceptable
bridge type	steel girders, prestressed and reinforced concrete beams, concrete slab	culverts, steel ortho-tropic decks
span length (m)	8 -20	4-8, 20-40
traffic density	Free traffic – no congestion (traffic jam)	
evenness of the pavement before and on the bridge	Class I or II (Table 10)	Class III (Table 10)
skew (°)	≤ 10	≤ 25

STEP 3. Checking WIM system before installation (chapters 6, 7.1, I-2, I-3 and II)

It is recommended to check WIM sensors and electronics before installation. Methods have been developed in some countries or are proposed by the vendors. The climate conditions, traffic conditions, mechanical resistance etc. should be taken into account. In addition, prior to the measurements the following facilities on the WIM site shall be checked:

- electricity supply,
- communication link,
- road side cabinet to protect WIM station against rainfall, snowfall etc.
- static weighing platform available or a static scale close to the WIM site.

STEP 4. Installation of WIM system (chapter II-4)

A WIM system installation requires special procedures depending for example on the type of sensors, the structure of the road, the type of bridges, the environmental conditions and the application.

STEP 5. Initial calibration of the system (chapters 7 and I-4)

Initial calibration must be performed before an operational use of WIM system. Choice of calibration method depends on the sensors type, the application and requirements of the user and the time and means available. Calibration methods described in COST 323 are:

- Static calibration,
- Use of shock or pressure variation devices,

- Use of pre-weighed calibration lorries,
- Use of instrumented calibration lorries,
- Automatic self-calibration procedure and software.

When the WIM system is intended to estimate the weights, the *Use of pre-weighed calibration lorries* is recommended. This method may be applied as follows:

1. Choice of test plan for initial calibration. A proper test plan according to COST 323 is required to be done in condition R1, Table 15, with at least three or four test vehicles, according to the traffic to be weighed (see 7.2.3.3 in COST323). It is also recommended to use one of the standard test plans described in Appendix I of COST 323. For all test plans, types of vehicles, speed, number of runs, loading, test program condition (r1, r2, R1, R2, Table 15) and confidence level (π0) are noted. However, specification allows also other test plans chosen according to customers (users) requirements and means.
2. Obtain static weights of calibration vehicles. Rules and clauses that should be applied in the case reference gross weights and axle loads measured in static are described in Chapter 8.3 of the COST 323 specifications.
3. Choose the method for calculating the calibration factor, which is defined as a multiplicative factor to be applied to a raw recorded “dynamic” value to get the final estimation of the static value (or “calibrated” results). COST 323 – Appendix III briefly described various methods that are commonly used.

STEP 6. Initial verification – checking accuracy (chapters 10 and I-7)

After installation and calibration of a WIM system, initial verification should be carried out to assess its accuracy. The same data can be used as for initial calibration. In the case of initial verification the confidence intervals given in Table 9 are reduced to 0.8δ for each relevant accuracy class and criterion. Initial verification can be applied as follows:

1. Provide WIM data for verification (gross weights, axles, axle groups, axles of groups). In the case of initial verification, the same sample can be used for calibration as well as for accuracy assessment. Calculate the relative errors with respect to the reference (static) values for each sub-populations (gross weights, axles, axle groups, axles of groups) and then calculate the mean (m) and the standard deviation (s) of the relative errors

   Calculate confidence level π using statistic results (m and s), sample size n and proposed accuracy class with confidence interval 0.8δ (δ is specified in Table 9 for different accuracy classes). Two methods for calculation of confidence level π are described in chapter 11.4.6. of COST 323.

2. Specify the minimum confidence level π_0 which is based on environmental conditions (I, II,III, Table 14), test conditions (r1, r2, R1, R2, Table 15) and sample size (*n*). Values π_0 are given in chapter 11.2 in COST 323. It is recommended to require –by the choice of the plan – a confidence level greater or equal to 90 % in reproducibility conditions (R1) and (R2), and greater or equal to 95% in repeatability conditions (r1) and (r2).
3. Perform test of acceptance. If $\pi > \pi_0$, the system is accepted in the class δ, otherwise, the system cannot be accepted in the proposed accuracy class, and the acceptance test is repeated with a lower accuracy class (a greater δ).

Table 14: Environmental conditions

I	**Environmental repeatability**	The test time period is limited to a couple of hours within a day or spread over a few consecutive days, such that the temperature, climatic and environmental conditions do not vary significantly during the measurements;
II	**Limited environmental reproducibility**	The test time period extends at least over a full week or several days spread over a month, such that the temperature, climatic and environmental conditions vary during measurements, but no seasonal effect has to be considered;
III	**Full environmental reproducibility**	The test time period extends over a whole year or more, or at least over several days spread all over a year, such that the temperature, climatic and environmental conditions vary during the measurements and all the site seasonal conditions are encountered;

Table 15: Test programme conditions

r1	**Full repeatability conditions**	If only one vehicle passes several times at the same speed, the same load and the same lateral position;
r2	**Extended repeatability conditions**	If only one vehicle passes several times at different speeds (according to the traffic lane conditions), different loads (e.g. fully loaded, half-loaded and empty) and with small lateral position variations (according to the real traffic paths);
R1	**Limited reproducibility conditions**	If a small set of vehicles (typically 2 to 10), representative of the whole traffic composition expected on the site (silhouettes and gross weights), is used, each of them passing several times, at different speeds, different loads and with small lateral position variations;
R2	**Full reproducibility conditions**	If a large sample of vehicles (i.e. some tens to a few hundred), taken from the traffic flow and representative of it, pass on the WIM system and are statically weighed before or after it.

STEP 7. In-service verification (chapters 10 and I-7)

An in-service verification of the WIM system should be done periodically, if traffic or environmental condition changes or if there is any doubt about the data accuracy. In such verification, the data used for the accuracy assessment must not have been used for any calibration or recalibration of the system. The procedure for in-service verification is similar to that of initial verification with two exceptions: (1) Test programme should be done to provide WIM data – choice of test plan is described in STEP 5 (in the case of initial verification, the WIM data have been obtained by initial calibration); and (2) confidence interval of required accuracy class given in Table 9 is not reduced, it is equal to δ. If the system fails the test of acceptability, the recalibration of the system is needed.

STEP 8. Data storage, processing and transmission (chapter 12)

It is out of the scope of COST 323 WIM specification to specify in too much detail the content, structure and format of the data files containing the WIM output. Only the detailed vehicle by vehicle data are considered.

3.2 Quality Assurance of WIM data and Cleaning Erroneous Data

All WIM systems produce a certain amount of erroneous data. Any analysis of WIM data must consider these errors in order to have confidence in the results obtained. These errors are not related to the accuracy classification of the system. Accuracy classes (COST323 2002) describe the weight measurement accuracy of the WIM sensor; however, the errors which will be discussed here relate to gross errors when recording axle weights and/or axle spacings. These erroneous measurements are often unexplainable but can sometimes be caused by a vehicle straddling both lanes or vehicles travelling closely together. Simple rules for identifying erroneous data will be described initially. These are a combination of rules previously proposed in different studies and aim to identify and remove any records which have incorrectly recorded the weights or axle spacings of a vehicle.

A Kernel Density Estimator approach for quality assurance of WIM data will also be described. This statistical approach is used to assign a probability to all possible axle configurations. This can then be used to flag erroneous configurations which will likely have a low probability of occurrence. This method can be used to complement the simple rules in order to flag erroneous records which may have been missed by these rules.

Calibration drift or loss of calibration will also be addressed. This involves the system consistently under- or over-weighing axles. Drift refers to a gradual increase or decrease in measurements with time. This is often associated with insufficient adjustment for seasonal changes in temperature. Monitoring techniques for identifying drift and loss of calibration in the WIM records are described.

3.2.1 Cleaning Erroneous WIM Records

Simple Rules

Many authors have developed methods for identifying erroneous WIM data. In an NCHRP report, Sivakumar et al. (2008) acknowledge that all WIM data contains a certain amount of erroneous data which must be removed before any meaningful statistical analysis of the data can be performed. A set of filtering rules is described for identifying and removing such records from the database. These rules primarily focus on checking each record to determine if parameters such as speed, axle spacing and axle weights are within certain expected ranges. Enright & OBrien (2011) describe a set of cleaning rules which are similar to those of Sivakumar et al. (2008) but, in addition, they describe a points system where by a WIM record accumulates points for each rule which identifies it. If the total number of points exceeds a certain level then the record is removed. This points system approach is also adopted by Leahy (2013) with some minor modifications.

Table 16 shows a list of cleaning rules which are taken from mainly from Enright & OBrien (2011) with some additional rules taken from Leahy (2013). If a record accumulates seven points or more, it is removed from the database. If it is not desirable to remove records from the database, then a flagging approach could be adopted. This approach was adopted in the BridgeMon project (Corbally et al. 2014). The same rules are applied but a flag is assigned based on the number of cumulative points – see Table 17.

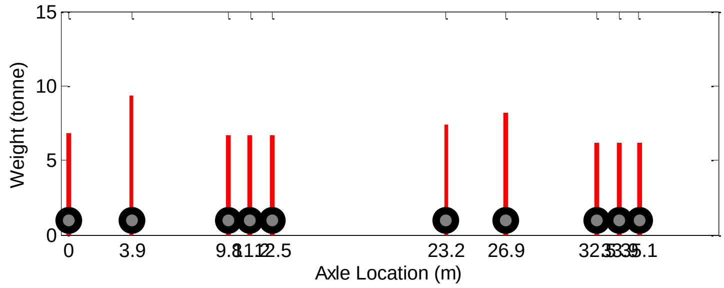
Table 16: Rules for identifying erroneous data.

Criterion	Change in Score
Wheelbase < 1 m	+7
Wheelbase < 30 m & 1st or last spacing > 10 m	+7
Wheelbase > 40 m	+7
Trucks with axle load <= 0 t	+7
Any axle weight > 40 t	+7
Any axle weight > 15 t & > 85% of gross weight	+7
Trucks with gross weight <= 0 t	+7
Sum of axle loads not within 50 kg of gross weight	+7
Truck with closely spaced (<= 2 m) first two axles, one of which is > 10 t and over 2.5 times heavier than other axle.	+7
1st spacing > 15 m	+7
Any spacing < 0.4 m	+7
Number of axle spacings doesn’t agree with number of axle loads	+7
Sum of axle spacings not within 50 mm of wheelbase	+7
Number of axles <= 1	+7
Duplicate records (remove duplicates)	+7
First axle spacing > 10 m & <= 15 m	+4
Each spacing in range 0.4 – 0.7 m	+2
Each spacing in range 0.7 – 1.0 m	+1
Each axle load in range 25 – 40 t	+2
Each axle load < 0.5 t	+2

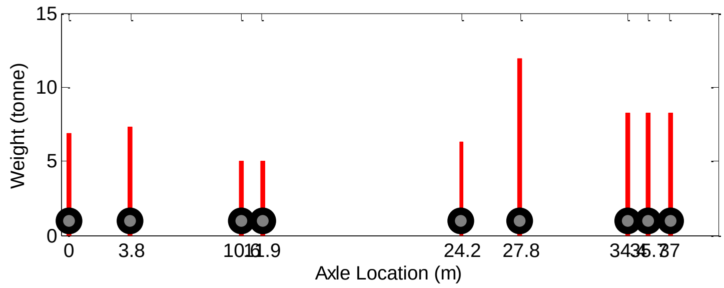
Table 17: Flags for suspicious WIM records

Flag Colour	Points	Description
Green	0	Good record. No suspicious characteristics detected.
Orange	< 7	Suspicious record. Some suspicious characteristics detected which would suggest that this record may be erroneous.
Red	≥ 7	Very suspicious characteristics detected which would indicate that this record is most likely erroneous and should be cleaned from the data.

Another type of error which can occur when two trucks are travelling closely together at identical speed is that both trucks are recorded as one vehicle record rather than two. Examples of such records are shown in Figure 26. These records can be identified by searching for WIM records with a relatively long axle distance present somewhere in the middle of the record and the front and rear parts correspond to a predefined vehicle class. Once one of these records has been identified, it can be split and replaced in the database with two separate vehicle records.



(a) Two five-axle semi-trailers.



(b) A four-axle semi-trailer followed by a five-axle semi-trailer.

Figure 26: Examples of WIM records consisting of two trucks recorded as one.

A Kernel Density Approach for Identifying Erroneous WIM Data

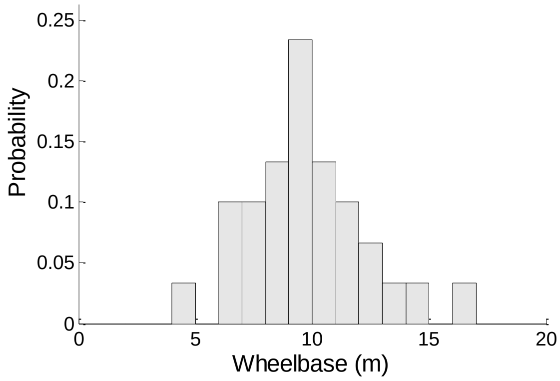
Kernel Density Estimation is a statistical technique for fitting a probability distribution to a set of data. This approach can be used to complement the simple rules in the previous section in order to identify erroneous or suspicious records which may not have been identified by the simple rules. The use of this method for quality assurance of WIM data was first proposed by Corbally et al. (2014). It is demonstrated here using simple examples.

Kernel Density Estimation (Silverman 1986) involves fitting a continuous distribution to sample data. Each sample data point is replaced with a component distribution which is called a 'kernel function'. These distributions are then added to obtain a complete probability density function. Any distribution can be used for the kernel function but a normal distribution is probably the most common and is used here.

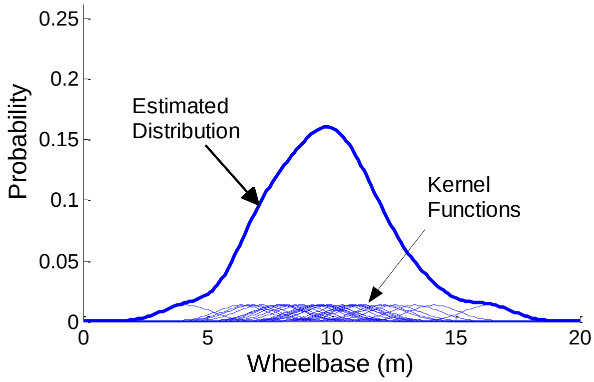
Figure 27 shows a simple example of how the method works using 30 measured wheelbase values. Figure 27 (a) shows a histogram of the 30 sample values. Figure 27 (b) then shows the kernel functions which replace each of the sample data points. The area under each of these functions is 1/30 and they are added to obtain an estimate of the probability density function for the data. In Figure 27 (c), this distribution is shown alongside the histogram of the sample data. It can be seen that the estimated distribution achieves a good fit to the data while smoothing the random 'bumpiness' in the histogram and extrapolating beyond the bounds of the measured data.

Demonstrating the Kernel Density Approach for WIM quality assurance

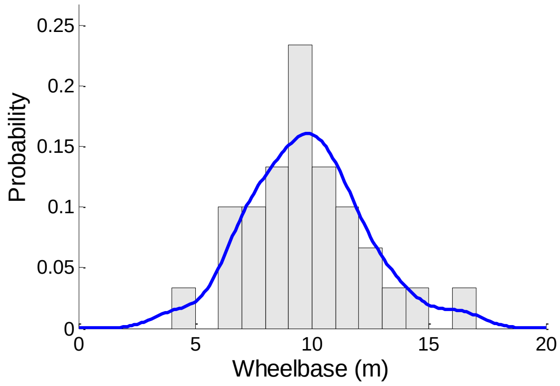
The Kernel Density approach for quality assurance is demonstrated here with reference to axle spacing measurements for three-axle trucks. Three-axle trucks are used as they have two spacings/variables and the resulting distribution can be easily visualised. This is not the case for trucks with more axle spacings as the multidimensional distribution of probabilities has more than two variables. The approach can be applied in a similar way for axle weights.



(a) Histogram.



(b) Kernel functions used to estimate distribution.



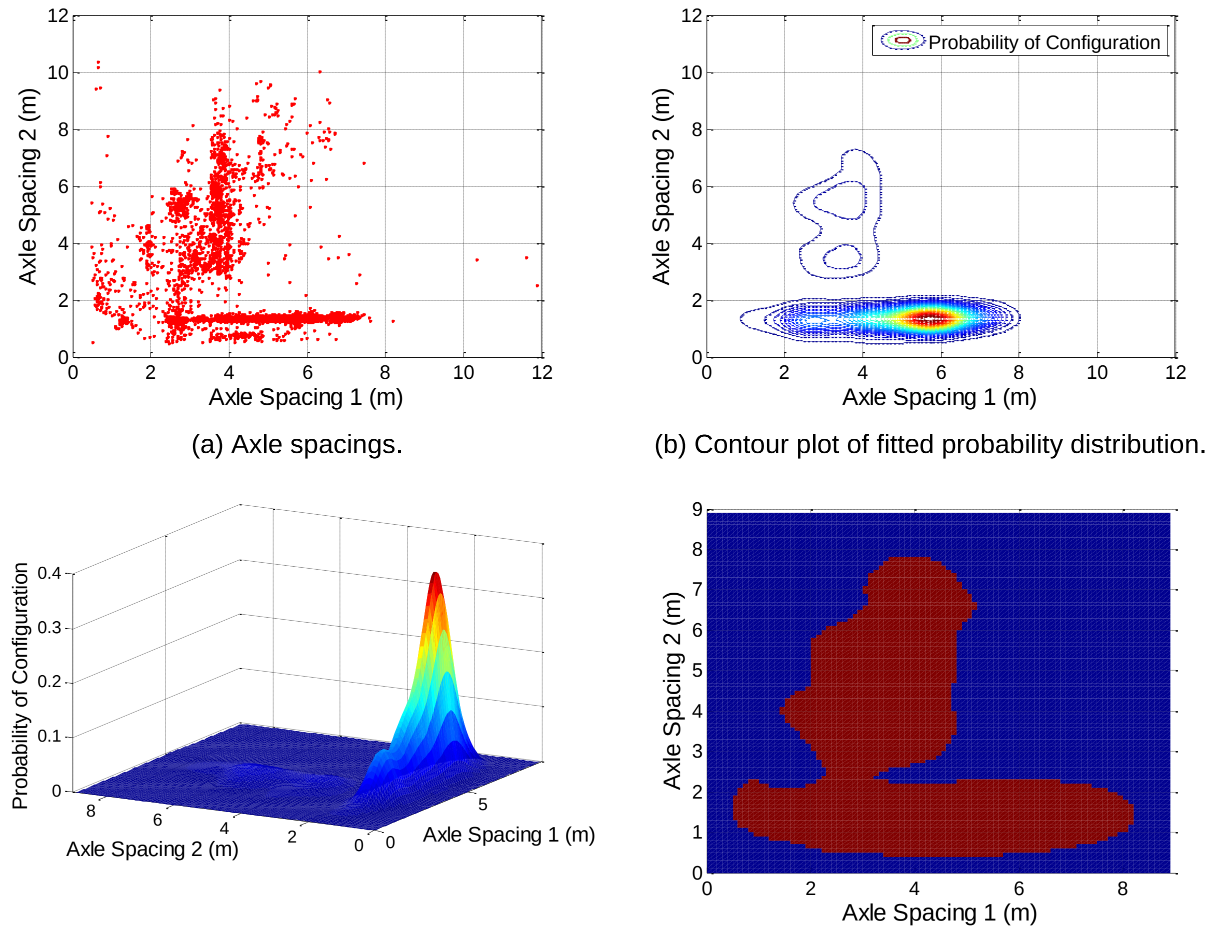
(c) Histogram alongside estimated distribution.

Figure 27: Kernel Density approach applied to 30 sample wheelbase values.

Figure 28 (a) shows the axle spacing configurations for 10,000 three-axle trucks which are randomly sampled from a UK WIM database. It can be seen that there is a horizontal band at the bottom of the figure which represents trucks with a tandem at the rear of the truck. This is the most common type of configuration for the last two axles in 3-axle trucks. These common axle configurations are also clearly visible in the fitted Kernel Density Estimated distribution which is fitted to the data and shown in Figure 28 (b) and (c).

This fitted distribution gives the probability of occurrence of all possible axle configurations. In order to use this distribution for quality assurance, a threshold probability level must be decided upon, below which a vehicle is either flagged as suspicious or removed from the database. As an example, Figure 28 (d) shows all axle configurations in the 5th percentile (less than 5% probability) in blue. The concept is that all data in the blue zone would be identified as suspicious as it is an unusual configuration.

As the number of axles on the truck being examined increases, the number of variables in the probability distribution also increases. For example, five-axle trucks have four variables for axle spacings. As a result, a multidimensional matrix of probabilities must be created and as the number of axles increases, the matrix size increases exponentially. This means that there is a limitation on the maximum number of axles for which this method can be applied. The findings in Corbally et al. (2014) would suggest that six-axle trucks can be examined with today's computers. As the vast majority of trucks have six axles or less, this would suggest that this method may be very useful for standard trucks but may not be applicable to trucks with more than six axles, the majority of which may be special permit trucks.



(a) Axle spacings.

(b) Contour plot of fitted probability distribution.

(c) Surface plot of fitted probability distribution.

(d) Blue area shows the axle configuration in the 5^{th} percentile.

Figure 28: The Kernel Density Estimated distribution for a sample of 10,000 three-axle trucks.

3.2.2 Live Monitoring of the Calibration of a WIM Site

Live monitoring involves a general examination of the measurements recorded by a WIM system, rather than examining each individual vehicle record. These checks aim to determine if a WIM system is working as intended and recording properly calibrated data. The data is analysed to determine if certain statistics, such as weight histograms and proportions of certain truck classes, are as expected.

Detecting Loss of Calibration

COST 323 (2002) defines testing methods for determining the accuracy class of a WIM system. The results will give the accuracy of a WIM system at the time of testing. However, calibration can gradually drift with time or can even be suddenly lost. This can be caused by factors such as seasonal temperature changes, pavement degradation or faults within the system. Methods are outlined here to identify calibration drift or loss of calibration.

Grundy et al. (2002), amongst others, recognised that the steer-axle weight on a five-axle semi-trailer truck is useful for identifying calibration drift. As the weight of this axle is not greatly influenced by the payload of the truck, it varies little about a mean value. As a result, the average weight of these axles can be monitored to identify drift over time. Figure 29 shows the steer-axle weights for 5-axle trucks at a WIM site in Ireland. The mean daily weight is shown for the main driving lanes and the mean weekly weight is used for the overtaking lanes. Mean weekly weight is used for the overtaking lanes as they experience lower flows and the statistics are more affected by random variation in the data. The use of mean weekly data smoothes out some of this random variation in the overtaking lanes. However, depending on the flow in these lanes, some random variation may still be apparent in the results. It can be seen in Figure 29 that the weights in the main driving lanes remain relatively constant for the first 70 days but towards the end of the period, some calibration drift appears to occur as weight readings increase. Seasonal increases in temperature may be responsible for this drift as the data is for the period of January through March.

Some WIM systems perform auto-calibration using the weights of the steer axles on five-axle trucks. As a result, a secondary weight check can be useful for these sites as no drift should be apparent when examining the steer axles on five-axle trucks. After an examination of different alternatives, Leahy (2013) found that monitoring the mean truck weight offered the best alternative. Figure 30 shows this statistic for the same Irish WIM site.

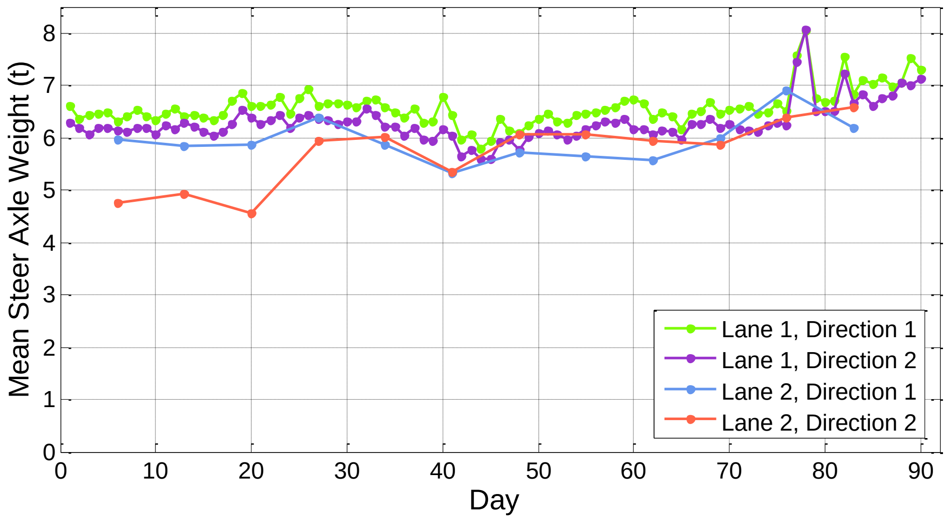


Figure 29: Mean steer axle weight on five-axle trucks at an Irish WIM site.

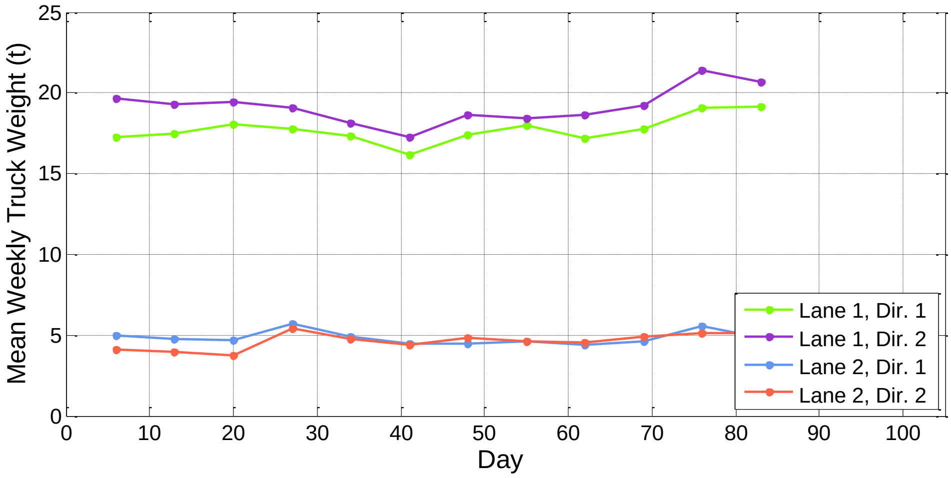


Figure 30: Mean weekly truck weight at an Irish WIM site.

It can be seen that the truck weights are significantly higher in the main driving lane as it carries the majority of heavy vehicles. However, it is the variation over time that is of interest rather than the absolute values. It is seen that the calibration drift which was found in Figure 30 for the main driving lanes in both directions is also seen for the mean trucks weight statistics while there is no noticeable drift detected in the overtaking lanes.

Axle spacing can be monitored by examining the rearmost axle spacing on five-axle trucks. This spacing is generally part of a tandem or tridem which both have regular spacings of about 1.35 m. A histogram of these spacings is shown in Figure 31 and the peak in the histogram can be clearly identified at 1.35 m. If the peak of the histogram moves from this position, it is an indicator that axle spacings are not being recorded correctly.

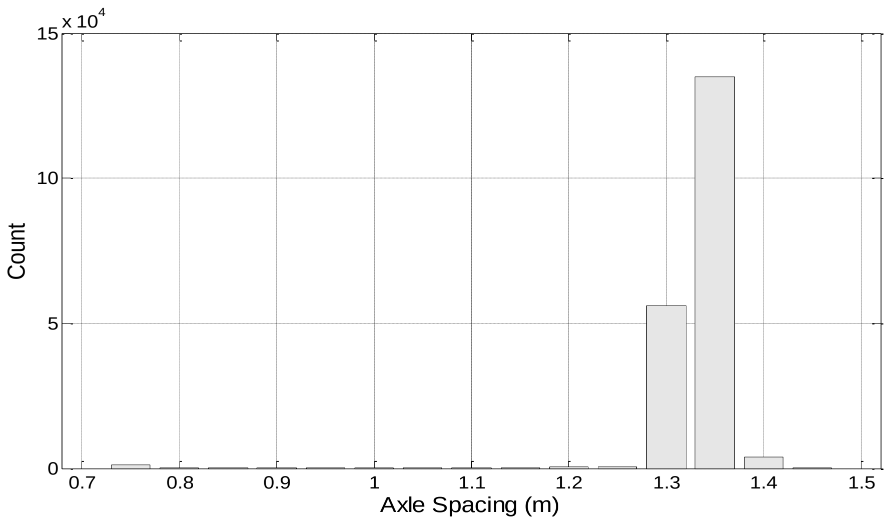


Figure 31: Histogram of rearmost axle spacing on five-axle trucks at an Irish WIM site.

LTPP Checks

The Long Term Pavement Performance (LTPP) program in the United States has been collecting WIM data for over 25 years (Walker & Cebon 2012). They have developed a set of nine quality assurance checks for their WIM data. The checks aim to identify any abnormal behaviour of their WIM systems. A particular focus of the checks is to examine the statistics for Class 9 trucks (five-axle semi-trailers) as they are the most common truck class in the United States. The checks only examine the data for weekdays as traffic characteristics are different at weekends and public holidays:

1. Total daily count by vehicle.
2. No lane has a value of 0 in a specific hour.
3. No lane has a traffic count of 2,500 or more in any specific hour.
4. Percentage of vehicles with an error per day.
5. Percentage of status clear vehicles per day.
6. Total daily count of Class 9 vehicles.
7. Percentage of Class 9 vehicles per day.
8. Percent warning count of Class 9 vehicles per day.
9. Average gross vehicle weight of Class 9 vehicles per day.

3.3 Examples of good practice of using WIM data for bridge applications

Accurate estimates of characteristic lifetime maximum traffic load effects are required for the accurate design and assessment of bridges. For the short to medium span bridges which will be discussed here, free flowing traffic is critical and the critical events on short to medium span bridges generally consist of a single very heavy truck on the bridge or a meeting event where two or three less heavy trucks are on the bridge simultaneously (Enright & OBrien 2013). On shorter span lengths, e.g. 5 – 10 m, the critical event may consist of only a group of axles on the bridge rather than the full trucks. For longer spans, i.e. over 50 m, the critical events tend to be governed by congested traffic where there are a large number of closely spaced vehicles on the bridge. To model such traffic, simple statistical methods, such as the Central Limit Theorem, can be used to determine the total load on the bridge but to determine bridge load effects, more complex microsimulation methods are often used (Caprani 2012; Enright et al. 2013). Modelling of congested traffic will not be directly discussed here but some of the free flow methods described can also be applied to congested traffic.

The most accurate method of determining characteristic bridge load effects is to use traffic data obtained from WIM. Statistical extrapolation is a popular approach for obtaining characteristic load effects from such data and the Generalised Extreme Value (GEV) distribution is commonly used. However, statistical extrapolation does not necessarily consider truck types and truck meeting events which were not recorded during the WIM measurement period. To address these shortfalls, long run simulations are often used to simulate many years of traffic crossing the bridge. This approach will generate new trucks and truck meeting events which were not measured during the WIM measuring period.

The guidelines described here outline how characteristic load effects can be estimated from WIM data. Some of the latest publications in this field are used to give examples of how these methods are applied to WIM data. Furthermore, some fast approximate methods, which allow rough estimates of characteristic load effects to be obtained without using complex statistical techniques, will also be discussed.

3.3.1 Extrapolation Using Extreme Value Distributions

Statistical extrapolation from measured WIM data to estimate the characteristic maximum lifetime bridge load effects has been used in many studies, both for site-specific assessment (Miao & Chan 2002; Getachew & OBrien 2007) and for the development of load models for bridge design (Nowak 1999; EC1 2003). Using a Normal distribution for extrapolation was once a popular extrapolation approach and involved the measured data being plotted on Normal probability paper (Nowak 1993; Nowak & Hong 1991). However, the Generalised Extreme Value (GEV) distribution is more appropriate for maximum-per-day or maximum-per-week load effects and may be more common at present. The GEV family of distributions contains the Gumbel (type I), Fréchet (type II) and Weibull (type III) distributions. With this extreme value approach the distribution is fitted to block maxima, e.g., maximum daily or maximum weekly values. Some authors use the type I Gumbel distribution (O'Connor & Eichinger 2007; Cooper 1997), but the type III Weibull distribution is perhaps more common in the literature (Bailey & Bez 1999; Miao & Chan 2002; OBrien et al. 2010; Graves et al. 2000). The Weibull distribution is bounded by an upper limit and would seem appropriate for modelling truck loads as there is an upper limit to the amount of weight that can be carried by a truck axle.

The Peaks Over Threshold (POT) is an alternative to the block maxima approach – all load effects greater than a specified threshold value are retained and fitted to a Generalised Pareto distribution. However, judgement is required to select an appropriate threshold – too high excludes good data and too low allows the main body of the distribution to interfere with the all-important trend in the tail.

The Rice formula is an indirect approach where the up crossing frequencies (rather than load effect data itself) are fitted to the formula. This is favoured in some countries and, notably, was used in the calibration studies for the development of the Eurocode (EN 1991 - Eurocode 1, 2009) for bridge traffic loading.

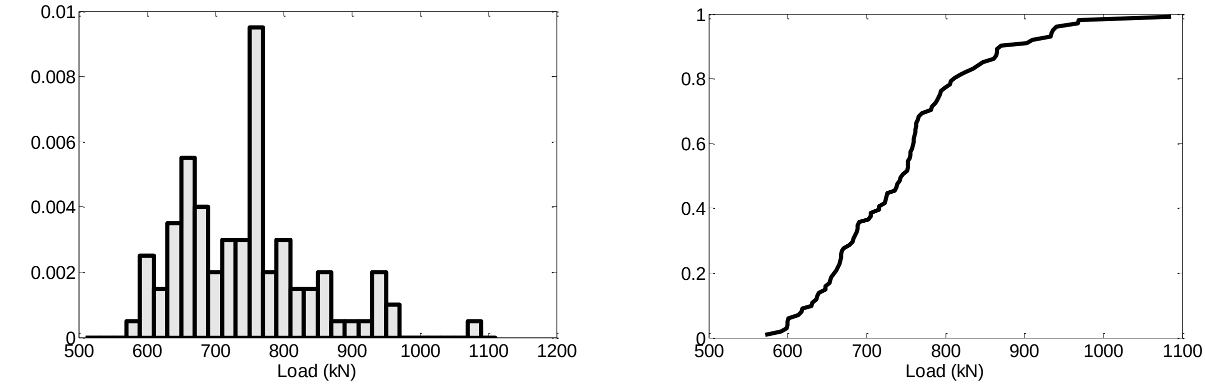
OBrien et al. (2015) review seven methods of statistical inference for bridge safety evaluation. They find that GEV and POT are generally good for inferring characteristic values. While they are less satisfactory from a theoretical viewpoint, fitting to a Normal distribution and the Rice formula also performed well in numerical tests. It can be concluded that the accuracy of the results is not very sensitive to the method chosen but are sensitive to the quantity of data used and the assumptions made with regard to the tail.

In order to visually examine extreme value data, it is often plotted on probability paper. This allows the behaviour of the data to be easily examined in the extreme upper tail, which is of interest when examining bridge loading. Figure 32 explains how data is plotted on Gumbel probability paper using a simple example of maximum daily truck weights. Maximum daily load effects would be examined in the same way. Figure 32 (a) and (b) shows a histogram and cumulative distribution function (CDF) of maximum daily truck weights. The behaviour in the tail of the data is of interest but it is difficult to determine the trend from these plots. In order to gain further insight into the behaviour in the tail of the data, the CDF is plotted with the y-axis rescaled to a double log scale – Figure 32 (c). The trend in the tail of the data is now much clearer. This is called Gumbel probability paper as the type I Gumbel distribution will plot as a straight line on this graph.

Figure 33 shows an example of the three types of GEV distributions plotted as a regular CDF and on Gumbel probability paper. It can be seen that the Gumbel distribution plots as a straight line and the bounded nature of the Weibull distribution is also clear as it curves upwards as it approaches an upper asymptote. It can again be seen in this figure that the tail behaviour is much more apparent in the Gumbel probability paper plot than the regular CDF.

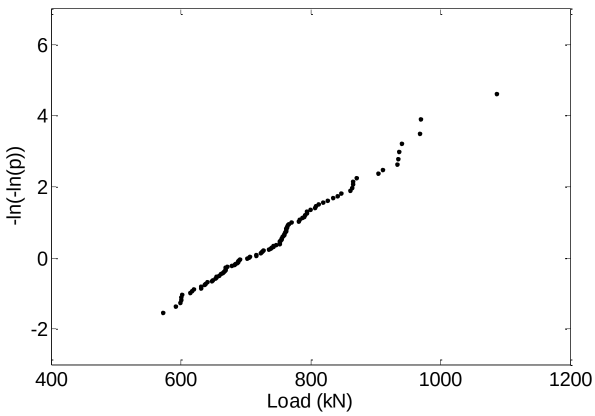
Bridge load effects (bending moments and shear forces), rather than the gross vehicle weights shown in Figure 32 and Figure 33, are generally of interest when assessing traffic loading on a bridge. The load effects for the measured WIM data must first be calculated by running the trains of trucks in the WIM data over the influence line for the load effect of interest. The maximum load effect for each day of data is then recorded. An extreme value distribution can then be fitted to these values.

When extrapolating beyond the tail of measured WIM data, the distribution is often only fitted to the tail of the data as this portion of the data is of most interest. OBrien et al. (2010) fit a Weibull distribution to the upper tail of the data, using the top $2\sqrt{n}$ data points as recommended by Castillo (1988). Others have fitted to the top 30% of data points (OBrien et al. 2015; Enright 2010). Figure 34 shows a Weibull distribution fitted to top $2\sqrt{n}$ maximum daily shear forces for a sample of WIM data. This distribution can then be used to extrapolate to the return period required for design/assessment (e.g. 50, 75 or 1000 years).



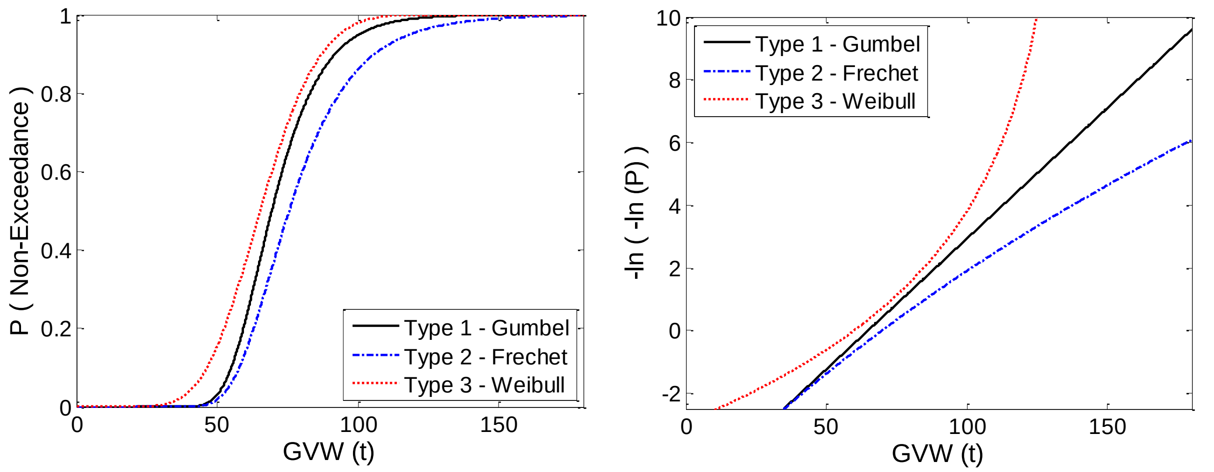
(a) Histogram

(b) Cumulative distribution function



(c) Probability paper

Figure 32: Example which uses maximum daily truck weights to show how data is plotted on Gumbel probability paper.



(a) Regular arithmetic y-axis scale

(b) Gumbel probability paper

Figure 33: The CDF of type I, II and III GEV data, plotted with an arithmetic y-axis and on Gumbel probability paper.

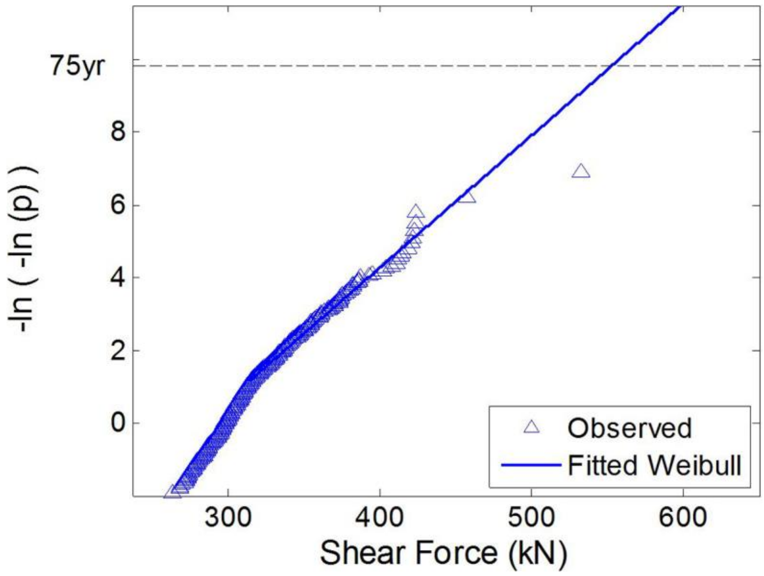


Figure 34: Probability paper plot of maximum daily shear force effects at the support of a 30 m simply supported bridge with fitted Weibull distribution.

It is known that changes can occur in the trend of a probability paper plot (e.g., around 320 kN in Figure 21). Rare events can emerge at higher return periods that were not apparent in smaller samples of data. It is important that any such trend be identified and the fit should be made to the tail beyond the point where the new trend emerges.

Filtering permit trucks

Another important issue which has a significant impact on bridge loading is permit trucks. Permit trucks are trucks which exceed the legal limit for weight and/or size and must apply for a special permit to use a road or road network. It has been shown that the maximum characteristic load effects on short to medium span bridges are caused by loading events which involve very heavy trucks (Enright & OBrien 2013). However, it is unclear whether these are permit trucks or illegally overloaded standard trucks. Most studies make no distinction between standard and permit trucks in their analysis (Bailey & Bez 1999; Nowak 1993; Crespo-Minguillón & Casas 1997) and other authors make simplifying assumptions to identify these trucks (Sivakumar et al. 2008).

Permit trucks should be identified in the WIM data as they are subject to more stringent controls and should arguably not be extrapolated to the same return periods as standard trucks. Some authors specify upper limits on gross weight limits, beyond which the truck is assumed to have a permit. However, this imposes an unnatural upper limit on weight with a consequent upper limit on most load effects. The result of this is an unnatural trend in the probability paper plots of load effects tending towards an asymptote – an artificial upper limit.

To avoid this problem, rules based on axle configuration have recently been developed (Leahy 2013; Enright et al. 2015) to separate the WIM records into apparent permit and apparent standard trucks. Apparent permit trucks generally consist of low loaders and crane type vehicles. The rules for identifying European permit trucks are summarised as follows:

A vehicle is classified as a low loader if it satisfies any of the following rules:

1. Has more than nine axles: In Europe nine axles is the maximum for European Modular System (EMS) vehicles.
2. Has the profile of a standard articulated truck, but is longer than the legal limit: Standard articulated trucks have one large spacing with more closely spaced axles before and after. This rule does not pick EMS trucks as they do not have a single large spacing.
3. Has a large truck length and group of four or more axles at back: A large truck length is defined as greater than the length limit for standard articulated trucks (16.5 m).
4. Has an overall length greater than 25.25 m (this is the maximum legal length): This is the maximum legal length in Europe.

A vehicle is classified as a crane type if it has more than two axles, a maximum spacing less than 4.5 m and an average spacing less than 2.5 m. 3- and 4-axle trucks are chosen only if their average axle weight is over 8 tonnes, to avoid choosing standard trucks with short wheelbases.

Figure 35 shows probability paper plots of the maximum daily truck weights at three European WIM sites. The filtering rules have been used to separate standard and permit trucks at these sites. It can be seen that the slope is greater for the apparent standard trucks as they have a natural upper weight limit.

This is not the case with the apparent permit trucks where the slope is less and they do not appear to converge to an upper limit. This can be attributed to the usual practice with these trucks of adding additional axles as the gross weight increases. In any calculation of characteristic load effects, apparent standard truck effects should be extrapolated to the specified return period. Apparent permit truck effects, on the other hand, should not be extrapolated at all (as they are controlled) or extrapolated to a smaller return period (to allow for illegal activities or poorly controlled permit issuing practices).

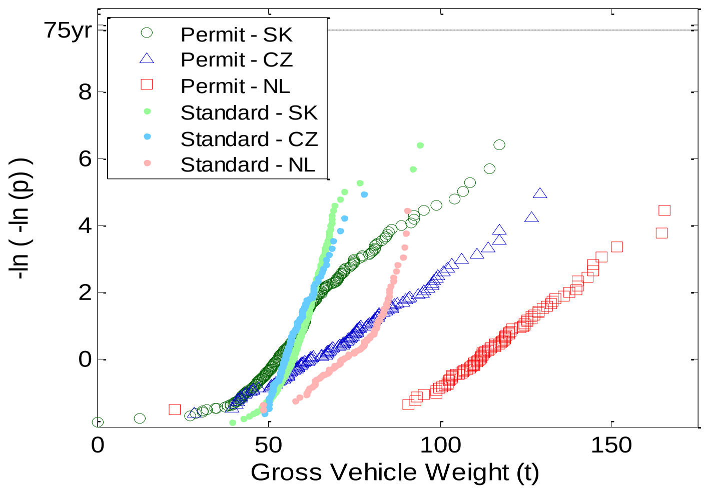


Figure 35: Maximum daily gross vehicle weight of permit and standard trucks at the three European WIM sites (from Leahy 2013).

3.3.2 Long Run Simulations

A Monte Carlo and Scenario Modelling approach to long run simulations will be discussed here and their applicability in different circumstances explained.

Monte Carlo Approach

Monte Carlo simulation is a method whereby random numbers are used to generate random data that is consistent with any specified probability distribution. For example, given the mean and standard deviation of the heights of a population of men, Monte Carlo simulation can generate a random population of men's heights that have that mean and standard deviation.

As described in Chapter 3.3.2, statistical extrapolation of the load effects generated by the WIM data is a popular method in the literature. A disadvantage of this method is that it may be overlooking certain axle configurations and multiple-truck loading events that are not captured in the WIM measuring period. To address this, Monte Carlo simulation methods can be used (Enright & OBrien 2013; Sivakumar et al. 2008; Kroese et al. 2011; Bailey & Bez 1999). Long-run simulations can generate hundreds or even thousands of years of traffic at a site. Over this simulated period, critical combinations of trucks, which may not have been measured in the WIM data, will be generated. Further, if the simulation allows for the generation of new truck configurations, it can simulate trucks which are heavier and have more axles than those in the measured data. Many studies have shown that characteristic load effects are sensitive to the quantity of WIM data used (e.g., less than one year of data). Monte Carlo simulation is one way to reduce the implications of using such small data sets.

In some cases, Monte Carlo simulations are used to enhance the WIM data and statistical extrapolation, may still be required to determine the characteristic loading for the required return period (e.g. 1000-year load effect). In other cases, thanks to the continuing increases in computing power, hundreds or thousands of years of traffic can be simulated crossing the bridge and the relevant load effects read directly from the simulations. This interpolation between simulated data is preferable to a shorter simulation which requires extrapolation.

In order to simulate new traffic, distributions are fitted to all parameters of the traffic and these distributions are used to simulate new traffic. Some of the relevant parameters which must be simulated include:

- gross vehicle weight,
- number of axles,
- axle spacing,
- weight distribution between axles,
- speed,
- inter-truck gaps,
- daily flow variations,
- proportion of each truck type.

Different statistical distributions are appropriate for different traffic characteristics. Figure 36 shows an example of how the tail of a bivariate normal distribution can be fitted to the heaviest measured GVW and number of axles, using truncated maximum likelihood estimation (Enright & OBrien 2013; Leahy 2013). In Monte Carlo simulation, this distribution can then be used to generate the GVW and the number of axles simultaneously. This allows for the simulation of trucks which are heavier and have more axles than those observed in a short WIM measuring period.

The Normal distribution is often used for many characteristics of the WIM data. Figure 37 shows an example of a Normal distribution fitted to the maximum-axle-spacing on low loader trucks. This is an important parameter for bridge loading, especially when calculating hogging moment over the central support of a two-span bridge.

Once statistical distributions have been fitted to all the relevant parameters, traffic can be simulated at a site. Figure 38 show an example of long run simulations performed for three European WIM sites, taken from Leahy (2013). It can be seen that the simulated data is a good fit to the load effects for the observed WIM data and effectively extrapolates beyond the WIM data.

Scenario Modelling

A Monte Carlo simulation approach performs well for single-lane traffic and two-lane bidirectional traffic, where the lanes are independent (Dissanayake & Karunananda 2008). However, two-lane same-direction traffic is more complex as truck weights and relative truck positions are correlated. For example, light trucks are more likely to be overtaking heavy trucks. Existing Monte Carlo simulation techniques do not account for these correlations. 'Scenario Modelling' is an alternative traffic simulation approach, proposed by OBrien and Enright (2011), which can reproduce these correlations during simulation. The method works by dividing the measured multi-lane WIM data into 'scenarios', i.e., clusters of vehicles adjacent to each other (Figure 26).

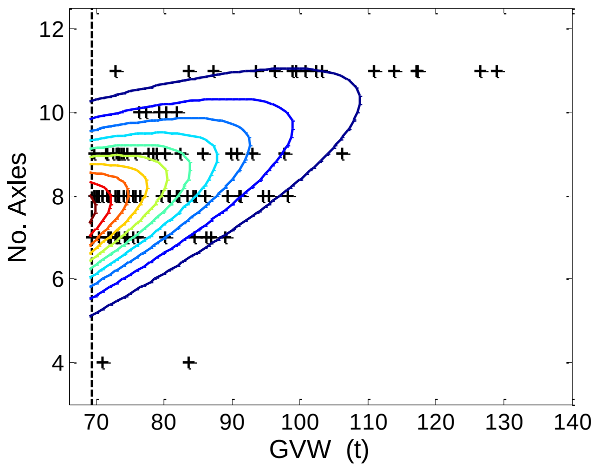


Figure 36: Contours of probability in the tail of measured WIM data using fitted bivariate (2-variable) Normal distribution.

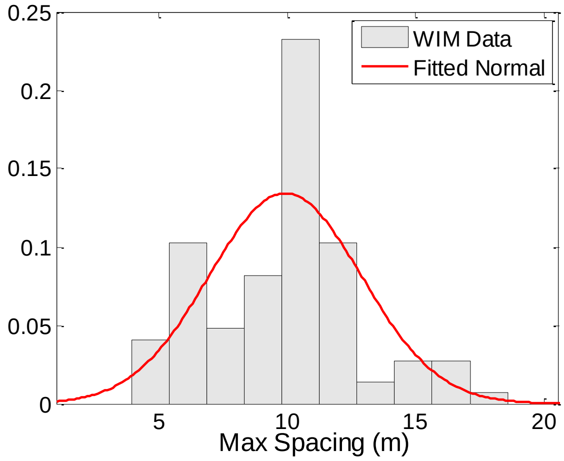


Figure 37: Maximum axle spacing for low loaders in Czech Republic WIM data.

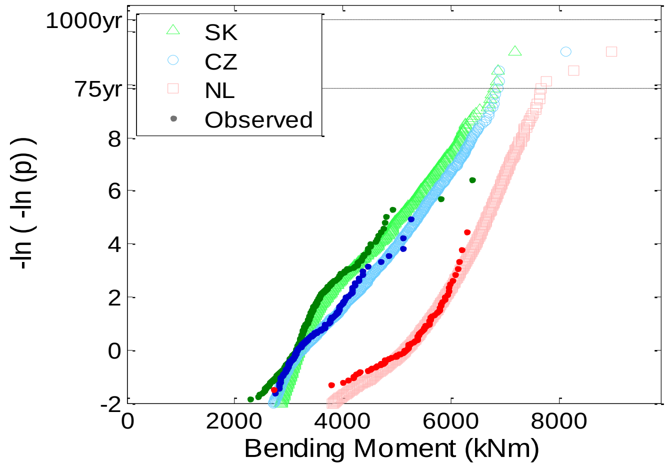


Figure 38: 300-year traffic simulations of bending moment on a 30 m bridge for 3 sites – dark colours are 'observed' from WIM while lighter ones are simulated.

To simulate traffic, scenarios are randomly selected from the WIM database and stitched together to generate new trains of vehicles. Each scenario is 'perturbed', i.e., small changes are introduced randomly in the truck weights and the relative spacings of the vehicles. This has the effect of better exploring the implications of small variations in the measured scenarios.

The perturbation was carried out by OBrien and Enright using a smoothed bootstrap approach (De Angelis & Young 1992) to generate new traffic which has been shown to maintain the correlations found in the measured scenarios. This process is then repeated to generate hundreds or thousands of years of traffic. Figure 39 demonstrates what is meant by a scenario and the relevant parameters that are varied during simulation. A scenario usually consists of five to eight slow lane trucks and any adjacent fast lane trucks.

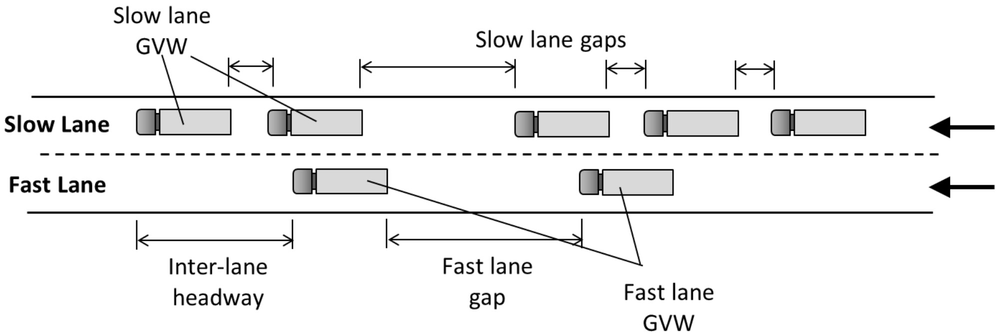


Figure 39: Sample scenario showing the properties which are varied in Scenario Modelling (GVW = gross vehicle weight).

3.3.3 Fast Approximate Methods

Although the methods described in Sections 3.3.2 and 3.3.3 are very effective for estimating extreme bridge load effects, they can be time consuming and require a certain amount of specialist knowledge. The fast approximate methods described here are aimed at allowing quick estimates of bridge loading to be estimated from WIM data without specialised statistical knowledge or training. They will give an indication of the characteristic maximum lifetime load effects.

Bridge Aggressiveness Index

The Bridge Aggressiveness Index (BAI) was developed by OBrien & Enright (2012). It uses WIM data to obtain a simple indicator which rates traffic in terms of its 'aggressiveness' for bridges, i.e., it indicates the magnitude of the load effects that the traffic will produce. The BAI is defined as:

BAI = 0.5 + [Mean weekly maximum GVW (t)] / 200 *(Eq. 1)*

The mean weekly maximum gross vehicle weight (GVW) is calculated by taking the maximum truck weight for each week of WIM data and then getting the average of these values.

This index was determined by OBrien & Enright (2012) using long run simulations for five WIM sites across Europe. Characteristic load effects were calculated for each site for a number of bridge lengths and load effects. It was found that the BAI correlated well with the Eurocode alpha factors calculated for each WIM site. Alpha factors are the ratios of the estimated characteristic load effects to the design load effects calculated using the basic traffic load model specified in the Eurocode (EC1 2003). This can be seen in Table 18 which is taken from OBrien & Enright (2012).

Table 18: BAI and alpha factors for each WIM site (from OBrien & Enright (2012)).

Site	NL	CZ	SI	PL	SK
Average alpha factor – all load effects, spans and lane factors	1.13	0.93	0.89	0.86	0.84
Mean weekly maximum GVW (t)	133.1	89.2	70.4	81.0	74.9
BAI	1.17	0.95	0.85	0.91	0.87

Convolution method

In Slovenia, the so-called convolution method described in Žnidarič et. al. (2012) was employed to calibrate the traffic load model for bridge assessment. This numerical technique is computationally far less demanding than a full simulation.

The method is based on work of Moses and Verma (1987) and Žnidarič and Moses (1997) and assumes that the highest load effects is achieved when two vehicles from independent traffic flows in each traffic lane are placed side by side on a bridge at the place of maximum action, which is defined as a loading event *E*. Such approach can be justified on short and medium span bridges with influence lines shorter then approximately 30 m (or even more on non-simply supported structures), where, due to the typical length of heavy vehicles, the critical event happens due to *one* vehicle in each of the two lanes. Such bridges comprise well over 90% of all bridges in Europe.

Knowing the influence lines, the time of vehicle entrance on the bridge and the axle loads and spacing, the expected load effects (moments or forces) are calculated from the superposition of the responses of each vehicle. The probabilities are then assembled in cumulative distribution histograms for one meeting event. Using the concept of extreme distributions (Ang & Tang, 1975), the probability distribution of the maximum response in a time period is written as a function of the number of events, *N*. N is calculated from the WIM database and is, as the entire convolution procedure, part of the SiWIM® system.

The computational procedure of the approach is divided into the following five steps:

1. Collection of weigh-in-motion data,
2. Calculation of load effects using influence lines, and generation of histograms,
3. Performing convolution of load effect histograms,
4. Evaluation of number of expected multiple-presence events on the critical section of the bridge,
5. Determination of convolution curves and from there, the maximum load effects.

Figure 40 shows the results of a test example from Slovenia obtained by the convolution approach, by University College Dublin (UCD) simulation procedure (the same data sample as used for Table 18), by NCHRP procedure - applying the normal distribution to model the tail (upper 5%) of the data (Sivakumar, Ghosn, & Moses, 2011) and by using raw WIM data (i.e. with measured data without modelling of the tail). The comparison of the results shows that the convolution procedure provides very similar estimates of traffic load effects, particularly for shorter periods when it can be assumed that traffic has not changed with respect to size and permitted weights of the vehicles, which were accounted for in the UCD simulation.

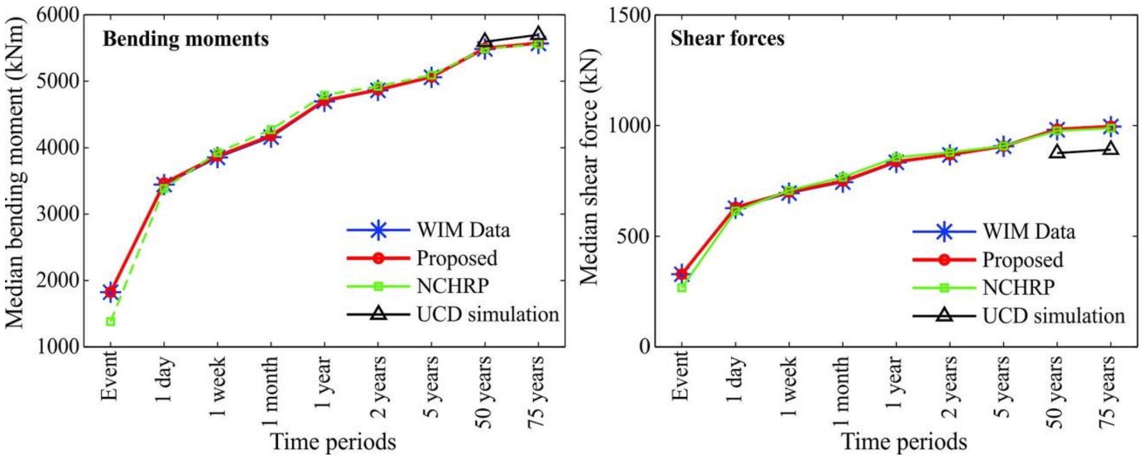


Figure 40: Median bending moments and shear forces for different time periods obtained by different procedures (from Žnidarič et. al. (2012))

A great benefit of using convolution method is its speed. On an average personal computer the results complied from a few months of WIM data equalling hundreds thousands of measured records are calculated in a matter of minutes. Furthermore, the convolution method is available as an add-on to the SiWIM® bridge weigh-in-motion system.

3.4 NCHRP REPORT 683 – Protocols for Collecting and Using Traffic Data in Bridge Design

In Europe, no recommendations exist on how to use WIM data for bridge applications. The only available practical guideline for collecting and using traffic data for this purpose is the American NCHRP Report 683 on *Protocols for collecting and using traffic data in bridge design* (Sivakumar, Ghosn, & Moses, 2011). This chapter provides a brief summary of this report, the full version with appendices can be found at www.TRB.org. This report focuses on the application of *available WIM data* for bridge design.

NCHRP Report 683 provides a set of protocols and methodologies for using traffic data to develop and calibrate vehicular loads for LRFD (Load and Resistance Factor Design) superstructure design, fatigue design, deck design, and design for overload permits. The protocols are geared to address the collection, processing, and use of national WIM data. The report also gives practical examples of implementing these protocols with different traffic exposures, load spectra, and truck configurations.

The report contains four chapters and six appendices. Chapter 1 gives a review of the problem statement, the research objective, and scope of study. Chapter 2 describes the research tasks, findings of the literature search and survey of states, a state-of-the-art summary, and the process to develop and calibrate bridge design live-load models. Chapter 3 provides the draft recommended protocols for using traffic data in bridge design and the results of the demonstration of the draft protocols using national WIM data. Chapter 4 contains the conclusions and recommendations for future research.

The recommended protocols are summarized as follows.

STEP 1. Define WIM Data Requirements for Live-Load Modelling

This step defines the types of traffic data and WIM sensor calibration statistics needed for live-load modelling of superstructure design load models (so called Strength I), overload permitting (so called Strength II), deck design, and calibration of fatigue load models.

STEP 2. Selections of WIM Sites for Collecting Traffic Data for Bridge Design

This step defines the criteria for selecting WIM sites for national, state-specific, route-specific, and site-specific design live-load modelling. Some of the criteria for selecting WIM sites include:

- remote WIM sites away from weigh stations with free-flowing traffic,
- sites that can provide a year’s worth of continuous data,
- sites that have been recently calibrated and are subject to a regular maintenance and quality assurance program, and
- sites equipped with current sensor and equipment technologies (preferably able to capture and record truck arrival times to the nearest 1/100th of a second or better).

STEP 3. Quantities of WIM Data Required for Load Modelling

Recommendations for the quantity of WIM data to be collected to capture the variability in traffic loads include:

1. A year of recent continuous data at each site to observe seasonal changes of vehicle weights and volumes;
2. A minimum of one month of data for each season for each site, if continuous data for a year is not available;
3. Data from all lanes in both directions of travel.

The most important parameters for load modelling are those that describe the shape of the tail end of the truck load effects histogram (the extreme values).

STEP 4. WIM Calibration and Verification Tests

WIM devices used for collecting data for live-load modelling should meet performance specifications for data accuracy and reliability. Field tests to verify that a WIM system is performing within the accuracy required is an important component of data quality assurance for bridge load modelling applications. Steps to ensuring this are:

1. Initial calibration of WIM equipment;
2. Periodic monitoring of the data reported by WIM systems as a means of detecting drift in the calibration of weight sensors; and
3. Periodic on-site calibration checks for long duration counts, where, in addition to Steps 1 and 2, the scale is subjected to periodic on-site calibration checks at least twice per year.

STEP 5. Protocols for Data Scrubbing, Data Quality Checks, and Statistical Adequacy of Traffic Data

High-speed WIM is prone to various errors that need to be recognized and considered in the data review process to edit out unreliable data and unlikely trucks to ensure that only quality data is used in the load modelling process. It is also important to recognize that unusual data are not all bad data. Ongoing simple quality checks are performed on the WIM data to detect any operational problems with the sensors (see section 3.2.1).

STEP 6. Generalised Multiple-Presence Statistics for Trucks as a Function of Traffic Volume

In many spans, the maximum lifetime truck-loading event is the result of more than one vehicle on the bridge at a time. Refined time stamps are critical to the accuracy of multiple- presence statistics for various truck loading cases including single, following and side-by-side. The relationship between the trucks' weights in the driving lane and overtaking lanes must be established to determine whether passing trucks' characteristics are similar to those in the driving traffic lane and if there is a correlation between the truck properties.

STEP 7. Protocols for WIM Data Analysis for One-Lane Load Effects for Superstructure Design

In this step, single-lane load effects for single truck events and for following truck events for superstructure design are determined. Load effects for following trucks may be obtained directly from the WIM data where accurate time stamps are collected. Generalized multiple-presence statistics obtained in Step 6 may be used for simulation of load effects where accurate truck arrival time stamps are not available. The trucks are grouped into bins by travel lane and run through moment and shear influence lines (or structural analysis program) for simple and two-span continuous spans.

STEP 8. Protocols for WIM Data Analysis for Two-Lane Load Effects for Superstructure Design

Here, the number of side-by-side multiple-presence events is determined, with trucks in adjacent lanes in each direction. Then the maximum daily load effects for two random trucks simultaneously crossing the bridge are evaluated, considering moment and shear influence lines for simple and two-span continuous spans. The results are normalized by dividing by the corresponding load effects for HL93 (the US reference loading scheme). Where accurate time arrival stamps are not available, generalized multiple-presence statistics obtained in Step 6 may be used for simulation of load effects.

STEP 9. Assemble Axle Load Histograms for Deck Design

As before, but with vehicles separated into Strength I and Strength II groups for single events and for two-lane loaded cases. For each group, axle load relative frequencies histograms are generated for single, tandem, triple and quadruple axles. Multiple-presence probabilities are determined for side-by-side axle events.

STEP 10. Filtering of WIM Sensor Errors/WIM Scatter from WIM Histograms

Current WIM systems are known to have certain levels of random measurement errors that may affect the accuracy of the load modelling results. This step proposes an approach to filter out WIM measurement errors from the collected WIM data histograms. To execute the filtering process, calibration data for the WIM system for a whole range of trucks should be obtained. The results of these sensor calibration tests are the basis for filtering out WIM measurement errors for each WIM data site.

STEP 11. Accumulated Fatigue Damage and Effective Gross Weight from WIM Data

Updating the LRFD fatigue load model using recent WIM data is described in this step. Damage accumulation laws such as Miner's Rule can be used to estimate the fatigue damage for the whole design period based on the truck population at a site. Cumulative fatigue damage is compared to the LRFD fatigue truck to determine the fatigue damage adjustment factor K. Based upon the results of the WIM study, changes may be proposed to the LRFD fatigue truck model, its axle configuration, and/or its effective weight.

STEP 12. Lifetime Maximum Load Effect L_{max} for Superstructure Design

In order to check the calibration of load models and/or load factors for strength design, it is necessary to estimate the mean maximum lifetime loading or load effect L_{max}. There are several possible methods available to calculate the maximum load effect for a bridge design period from truck WIM data. Simplified analytical methods or simulations may be used to estimate the maximum loading over a longer period (75 years) from short-term WIM data. The approach implemented in these protocols is found to be one of the easiest methods that provides results comparable to many other computationally intensive methods, including Monte Carlo simulations. This statistical projection method is based on the assumption that the tail end of the histogram of the maximum load effect over a given return period approaches a Gumbel (extreme value) distribution as the return period increases. This method is examined in chapter 3.3.1.

STEP 13. Develop and Calibrate Vehicular Load Models for Bridge Design

Various levels of complexity are available for utilizing the site-specific truck weight and traffic data to calibrate live-load models for bridge design. A simplified calibration approach (Method I) is proposed that focuses on the maximum live-load variable, L_{max} for updating the live-load model or the load factor for current traffic conditions, in a manner consistent with the LRFD calibration. The ratio, r (L_{max} WIM data, divided by L_{max} Ontario data) for one lane and for two lanes is used to adjust the live-load factor. This procedure assumes that the present LRFD calibration and safety indices are adequate for the load data and that the site-to-site variability (COV) of the present data and the data then available are consistent. A more robust reliability-based approach (Method II) also is presented that considers both the recent load data and the site-to-site variations in WIM data in the calibration of live loads.

4 Case Studies

This chapter demonstrates with cases studies from France, Ireland and Slovenia the importance of using WIM data for bridge application.

4.1 France – Millau bridge

The case of the Millau bridge highlights the importance of using WIM data for bridges where the codes do not apply. The design can then be verified using real traffic data.

4.1.1 Why using WIM data

The Millau Viaduct is a cable-stayed bridge that spans the valley of the River Tarn near Millau in southern France and carries the highway A75-A71 between Paris and Béziers/Montpellier, Figure 41.

Designed by the French structural engineer Michel Virlogeux and British architect Norman Foster, it is the tallest bridge in the world with the summit of one pylon at 343.0 metres above the base of the structure. The construction cost was approximately 400 million Euros.

The superstructure is composed of steel box-girders and has 8 spans. The steel parts (box and deck in particular) are orthotropic, Figure 42. This means that, apart from the extreme effects that have to be checked, the fatigue behaviour of the bridge and the design lifetime has to be checked.

The outer spans are 204 m long, whereas the interior spans are 342 m long, Figure 43. Due to span lengths in excess of 200m, Eurocode 1 classifies this structure as an exceptional one, in the sense that the load models given in these codes cannot be applied to this bridge.

Figure 41: Millau viaduct

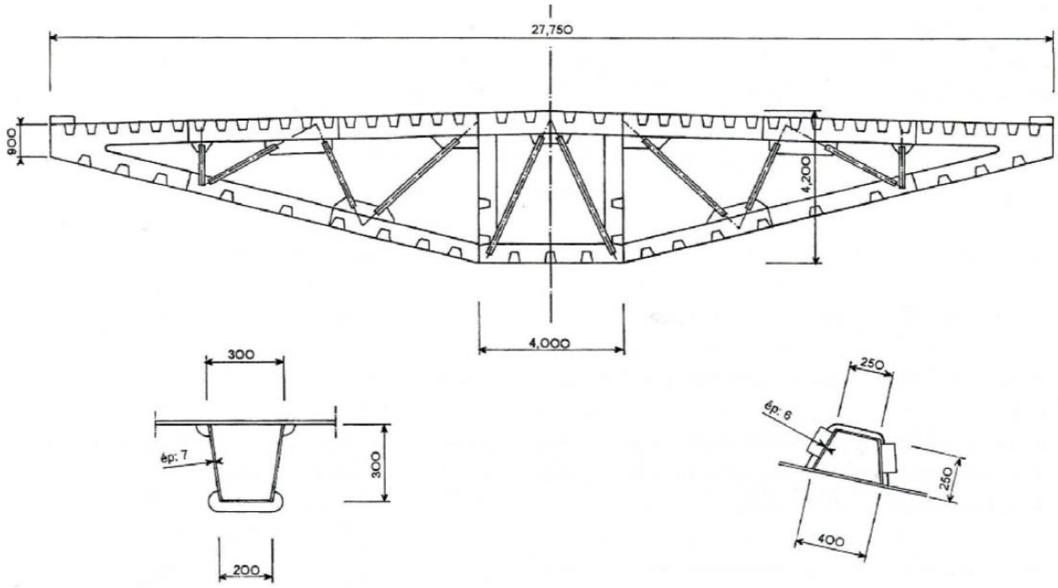


Figure 42: Transversal section of the Millau bridge.

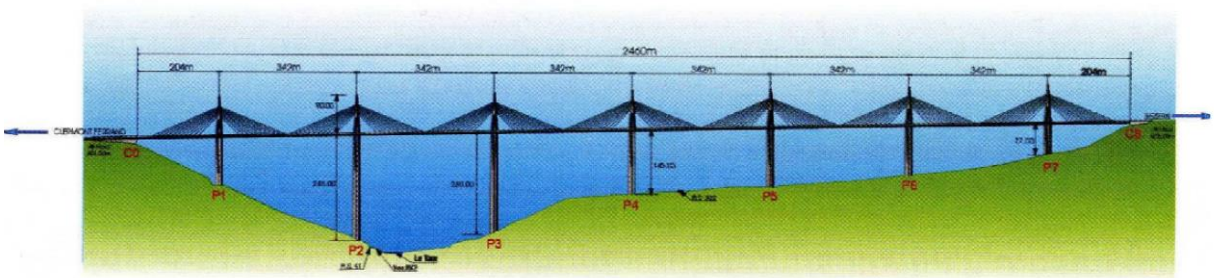


Figure 43: Longitudinal profile of Millau bridge.

Consequently, the loadings that the bridge will encounter during its lifetime have to be determined by other means and the behaviour of the bridge to the resulting forces has to be determined. For example, when considering wind actions, which are quite important in this part of France and at these heights, a wind tunnel testing programme was carried out.

For traffic loads, WIM data has been used to calculate the effect of traffic on several parts of the structure. Equally, the future traffic that will be driving on the four lanes (two lanes –one slow, one fast- in both directions) of the bridge was assumed.

4.1.2 Type of WIM data

Following a demand by Eiffage (builder of the Millau bridge), these calculations were carried out by IFSTTAR (formerly LCPC, Laboratoire Central des Ponts et Chaussées) in 2002.

Two WIM datasets were used:

- WIM data recorded on the four lanes of the A6 highway at Auxerre in the 1990s: this traffic was quite old, even in 2002, but it has been considered as important for two reasons: the first one was that it was still valid, meaning that it was still describing correctly the traffic of 2002. Equally, this traffic is important as it has been used in several studies and works: it has been used to calibrate the traffic loads part in Eurocode 1, it has been used in studies for design of Normandie bridge and Rion-Antirion bridge. It has been used by the German entity Bundesanstalt für Strassenwesen (BASt) to calibrate traffic loads for assessment of existing bridges.

- WIM data recorded on the two lanes of the Parisian ring road. This traffic data has a particular characteristic in that the fast lane is heavier than the slow lane because of the traffic regulations on this road (the right lane is just an insertion lane).

In the first part of the study, the A6 WIM data has been used directly to model the four lanes of the traffic on the Millau Bridge.

In the second part, and in order to cater for future increased traffic, the traffic on the fast lanes of Millau has been modeled by the heaviest lanes of the A6 traffic, whereas the traffic on the slow lanes has been represented by the heaviest lane of the Parisian ring road. As only one WIM data set existed for this heaviest lane (the fast lane) of the Parisian ring road, extra WIM data has been created through translation of the recorded data in time.

4.1.3 Overview of the analysis

Some effects on parts of the bridge had to be verified, Figure 44: the tensions in the cables for short, medium and long cables (sections 1301, 1305, 1309 and 1311 in Figure 44), the normal force in pile P6, the normal force in the pylon corresponding to pile P6, bending moment and normal force at various locations on the span P2-P3, rotations on support C8, rotations on the supports of pile P6, displacement at mid-span of span P2-P3.

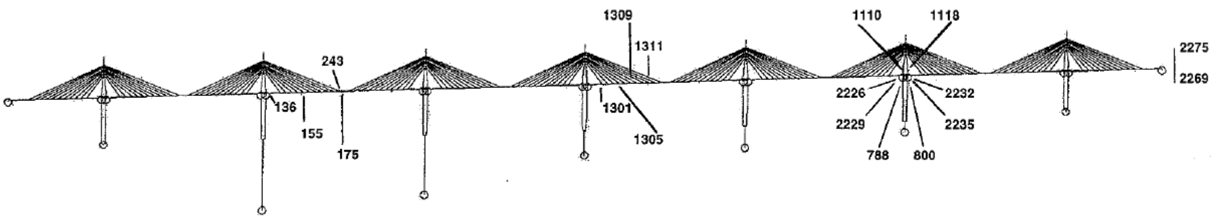


Figure 44: Studied sections.

The influence lines of these effects were provided by Eiffage to LCPC (an output of FEM carried out during the design stage), as for example in Figure 45. Thus, the effects encountered over time with the proposed traffics could be computed easily through convolution of these traffic and the influence lines.

Two types of outputs were provided:

- The extreme effects encountered by the bridge during its lifetime compared to the design effects.

  In order to calculate the extreme effects, the level crossings have been recorded and compared with Rice's formula (Rice 1954). Then, the underlying distribution function was determined through use of the Kolmogorov-Smirnov test. The methodology is the one exposed in (Crémona 2000).

  Then, using a distribution function, the 1000-year return level can be computed: it corresponds to the level that has a probability of 0.1% to be exceeded in one year, or 10% in 100 years. This return period of 1000 years is the period used in Eurocode 1 for designing structures regards traffic loads.

- The rainflow charts of the efforts in steel parts of the bridge were computed (Figure 46) and with the use of the Palmgren-Miner rule and the Wöhler curve (provided by Eiffage), the lifetime of the bridge was computed.

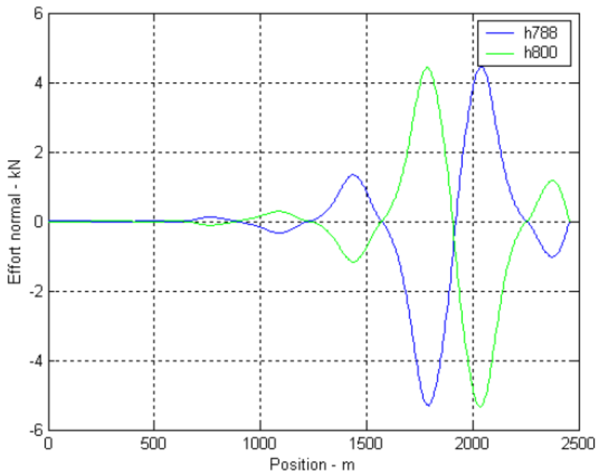


Figure 45: Influence line of the normal effort in pile P6, on two different locations.

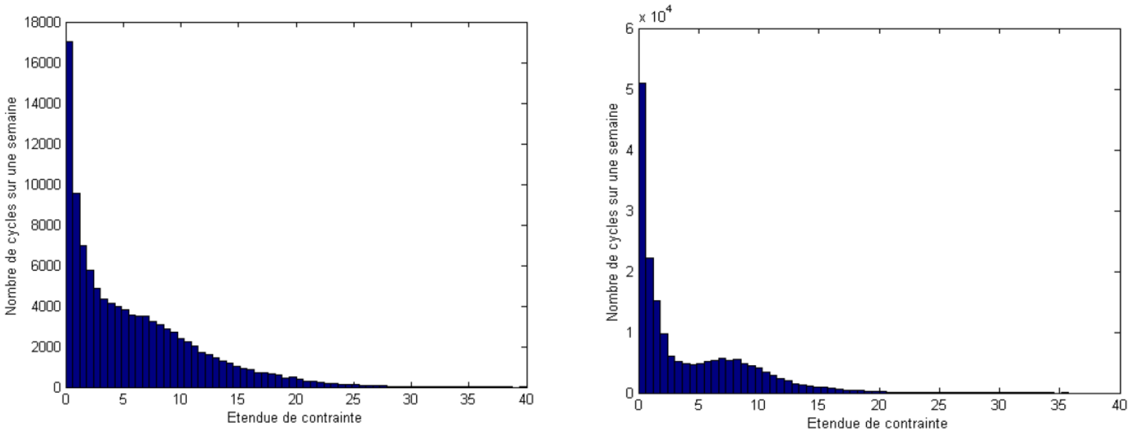


Figure 46: Rainflow diagram for the tension in the short cable, for the two traffic scenarios (Left: scenario A6, right: scenario A6 + ring road).

4.1.4 Conclusions of the study

Extreme effects

The calculated effects are approximately 80% lower than the ones obtained when applying the regulatory uniformly distributed load which is used in the load models of Eurocode 1, called A(l). This difference is decreased to 65% when looking at extreme values i.e. the extreme values obtained for the effects calculated with application of the WIM data are 65% lower than the extreme effects obtained with application of the regulatory load.

It is interesting to note that this is also the difference that has been observed between simulated effects and design effects for the bridges of Normandie and Rion-Antirion.

This first point highlights the importance of WIM data in order to assess precisely the effects induced by traffic. This is not only the case in the design phase of bridge, but also during assessment of existing bridges.

Another conclusion has been that the two traffic scenarios gave quite different results: the extreme effects obtained by application of traffic scenario 2 (A6 + ring road) are smaller than those obtained with the traffic A6. This shows the importance of using enough WIM data in order to have an estimation of the worst case (and thus the stability of the results).

Rainflow and fatigue

For the traffic scenarios that have been used, the cables and the assemblies are not prone to damage by fatigue, as the effect do not reach the endurance limit.

Nevertheless, these calculations give us only the effects of the global effect on various locations, and calculations of the effect of the local load of wheels on the upper part of the steel deck should be performed.

4.2 Using WIM data to justify an increase in legal weight limits in Ireland

Previous legal GVW limits for trucks in Ireland were 40 t on 5-axles (but with a temporary derogation of 42 t) and 44 t on 6-axles. In January 2011, Roughan O'Donovan Innovative Solutions (ROD-IS) were commissioned by the National Roads Authority of Ireland, on behalf of the Department of Transport, to undertake a study to investigate the impact of increasing the legal GVW limit on 6-axle trucks from 44 t to 46 t and making the 42 t derogation for 5-axle trucks permanent.

A study was carried out which ultimately aimed to investigate the likely impact that these changes would have on bridge safety and pavement damage. The study aimed to identify whether or not the codes used in Ireland for the design and assessment of bridges were sufficient to cover the proposed increase in loading on beam/slab and masonry arch bridges. In addition, the effect on pavement damage of removing the 42 t derogation was investigated, along with the effect of a move towards the use of 46 t 6-axle trucks.

In order to accurately assess the effects of the proposed changes, it was necessary to obtain detailed records of traffic loading, i.e. through the use of WIM data. At the time of the study, no WIM data was available for Ireland and as such, extensive WIM databases, primarily from Poland, were utilised for the analysis.

Using the WIM data it was possible to quantify the load effects induced in bridge structures by the measured traffic compared to load effects induced by the code loading. In this way, the effect on bridge safety of introducing the proposed changes to truck weights, could be estimated.

The study considered load effect ratios, computed as the ratio of the load effect induced in simulation to that induced by the considered codes of practice. These were calculated for each of the following loading models:

- <u>BD37/01</u> - used for the design of bridges in Ireland prior to April 2010 (Highways Agency 2001b)
- <u>Eurocode 1</u> - used for the design of bridges in Ireland after April 2010 (EC1 2003)
- <u>BD 21/01</u> - used for the assessment of bridges in Ireland (Highways Agency 2001)

The study also examined the effect of the changes on pavement damage, with the overall results of the work determining whether the proposed changes to the regulations governing truck weights were advisable.

4.2.1 Summary of WIM Data

In the absence of any Irish WIM records, a database from Poland was employed, along with five other databases across Europe which were used for the analysis of masonry arch bridges. The Polish data, recorded from a site located on the A4/E40 near Wroclaw, had the advantage of containing two lanes of traffic with both cars and trucks. It contained details of the traffic at the site for the first five months of 2008, with both weekday and weekend traffic for the two lanes being recorded. Weekend traffic is significantly lighter; both in volume and average gross vehicle weight (GVW) than weekday traffic and therefore this study focused on weekday traffic only, with an assumed 250 working days per year. This approach is more statistically valid than seeking to extrapolate characteristic lifetime loading from a mixture of different types of traffic. Table 19 provides an overview of the WIM data at the Polish site.

Table 19: Summary of Polish WIM Data

Vehicle type	Slow Lane[c]	Fast Lane	Total
Cars[a]	461,971	546,160	1,008,131
Trucks	320,511	27,226	347,737
Total	782,482[b]	573,386	1,355,868
% Cars	59.0%	95.3%	74.4%
% Trucks	41.0%	4.7%	25.6%

[a] A car is considered to be any vehicle with a GVW less than 3.5 t.
[b] 782,314 with less than 7 axles
[c] Slow lane traffic only was replicated to produce bidirectional traffic

Only traffic from the slow lane of the 2 + 2 site was used in the simulations carried out in this study. It is noted that this is a conservative assumption for a road consisting of two lanes of bi-directional traffic: if traffic transfers from two same-direction lanes into one, there will be a reduced density of heavy trucks as the slow and fast lanes mix.

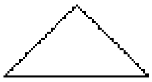
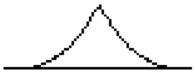
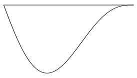
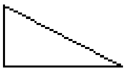
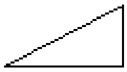
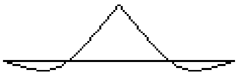
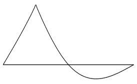
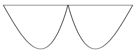
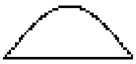
4.2.2 Overview of the Analysis

The analysis was divided into two distinct phases (i) Phase 1 - preliminary screening and (ii) Phase 2 – detailed analysis. The first phase consisted of a conservative analysis for a range of bridges to identify which structures and load effects were likely to be most critical. The second phase of the analysis focused on the critical load effects identified in Phase 1 and used the WIM data to carry out a more refined analysis to examine the likely effects of the proposed weight limit changes on bridge safety.

Phase 1 – Preliminary Screening

In the initial phase of the study, eleven influence lines were considered, outlined in Table 20, for bridge lengths of 7.5, 10, 15, 20, 30, 50, 75, 100, 125, 150 and 200 m. These influence lines were chosen as they formed the basis of the original Eurocode calibration exercise (O’Connor et al. 2001).

Table 20: Influence Lines

Influence Line Number	Representation		Description of the Influence Line
I0			Total load.
I1, I2			Maximum bending moment of a simply supported and double fixed[1] span, respectively.
I3			Maximum bending moment at the support of the former double fixed beam[1].
I4, I5			Shear force at the ends of simply supported bridge (assuming traffic flowing left to right)
I6			Moment at centre of central span in 3-span bridge with span ratios 0.7L:1.0L:0.7L
I7[2], I8			Minimum and maximum bending moment at mid-span of the first of two spans of a two span continuous beam.
I9			Continuous support moment of the former two span beam.
I10			Continuous support reaction of the former two span beam.

[1] with an inertia strongly varying between mid-span and the ends
[2] the second span only is loaded

The theoretical worst case scenario, i.e. convoys of fully loaded trucks, was modelled with the configurations and axle weights of fully loaded 5-axle and 6-axle trucks (i.e. 40 t/42 t on five axles and 44 t/46 t on six axles) taken from typical observed truck configurations. Jammed and free-flowing traffic scenarios were considered. For short bridges (e.g. bridge length < 40 m) the maximum load effect can result from either the free-flowing (including dynamics) or jammed scenario (without dynamics), depending on the load effect (Flint & Jacob 1996; O'Connor & OBrien 2005). Over 40 m, jammed scenarios generally govern. Hence, for bridges up to a length of 50 m, free-flowing conditions were simulated. This involved multiplying the static load effects by a Dynamic Amplification Factor (DAF), with the magnitudes employed in the Eurocode calibration, as shown in Figure 47. The DAF takes into account the dynamic amplification of static loads on a bridge due to vehicle-bridge interaction. For the free-flowing scenarios, a back-axle-to-front-axle gap of 25 m was assumed. For the jammed simulations, a 5 m gap was employed (Novak, 1994).

The results of the preliminary screening simulations showed that influence line I3 (Table 7) had the highest load effects compared to the code loading and was therefore considered in the detailed analysis along with influence lines I1 and I9 which were also shown to be more critical than the other influence lines. I4 was included to allow consideration of shear force effects.

Due to the prevalence of masonry arch bridges on Irish roads, and the inability to accurately describe the behaviour of these structures through the use of influence lines, a separate analysis was carried out to consider these structures. Twenty different geometric configurations of single span masonry arches, ranging from 5 m to 20 m were analysed using a specialised computer program for the analysis of arch bridges, *Archie-M*.

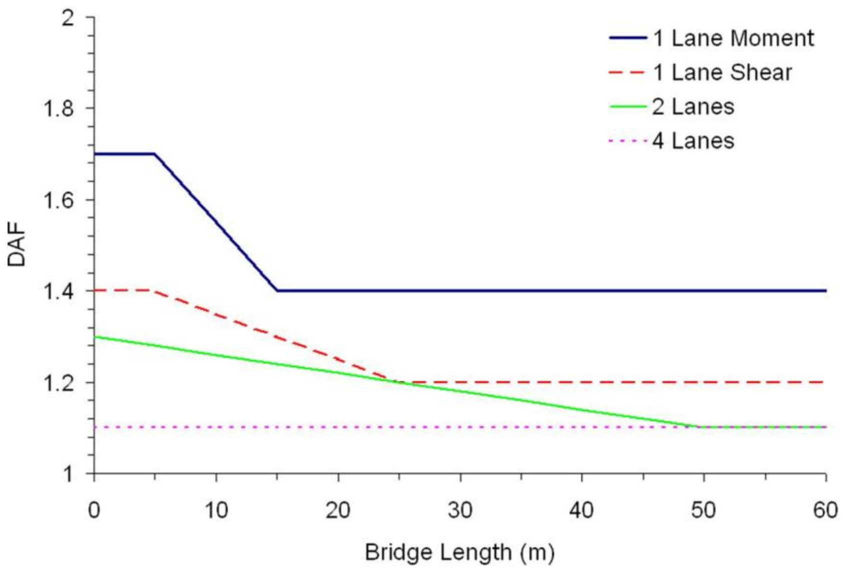


Figure 47: Dynamic Amplification Factors from Eurocode 1 (O'Connor et al. 2001)

The load effects calculated during the preliminary screening simulations were compared to those induced by the code load models, allowing the most critical structures and load effects to be identified. It is noted that in the case of the masonry arch bridges, the only code load model analysed, and used for the purpose of comparison, related to the assessment loading model prescribed by BD 21/01 since it alone allows application of single and group axle loads for the assessment of arch bridges. Therefore the critical axle group loading from each truck silhouette was applied to the arches to allow a valid comparison to the code.

The results of the simulations for masonry arches indicated, for a number of the arch geometries considered, that the load effects induced by the observed tridems on the 46 t trucks in the data were more severe than the basic 24 t tridem in the assessment code (BD21/01) which was shown to be dominant for the arches considered. As such it was considered a more appropriate comparison to calculate the characteristic tridem (i.e. the 1 in 1000 year tridem weight) and compare this to the factored code loading (1.9 × 24 t). It was found that these characteristic tridems did not exceed the factored code loading.

Phase 2 – Detailed Analysis

For the critical load effects identified in the Phase 1, detailed analysis was then carried out (i) using more appropriate traffic simulations and (ii) employing the statistics of extremes to model the results of these simulations for comparison with the values resulting from codified load models. The most critical influence lines, as identified by the preliminary simulations, were studied in greater detail. For the detailed analysis, more realistic traffic flow scenarios were modelled using the WIM data. Five alternative analyses were considered for the four critical influence lines, labelled A, B, C, D and E.

A. In the first analysis, the WIM data, without modification, was used to determine the characteristic load effects.

B. In each subsequent analysis (i.e. B-E), the data was modified by removing any truck with 7 or more axles on the basis that it was likely to be a permit (i.e. abnormal) truck. Simulations were therefore carried out, according to the following criteria:
C. No change to trucks with 6 or less axles.
D. Any 5-axle truck deemed to be fully loaded, i.e., with weight in the range 36 t to 42 t, was increased to 42 t.
E. Any 5-axle or 6-axle truck with weight in the range 36 t to 44 t was replaced with a 6 axle truck with weight 44 t.
F. Any 5 or 6-axle truck with weight in the range 36 t to 46 t was replaced with a 6-axle 46 t truck.

The output of the simulations consisted of daily maximum load effects for the four critical influence lines for each of the five scenarios considered. Using appropriate statistical methods, characteristic load effects for the various scenarios were calculated.

Scenario B was considered as the reference case (non-permit traffic), with scenario E being the most extreme (46 t trucks). Figure 48 shows the results of the extrapolation carried out for the mid-span bending moment on a 125 m bridge (influence line I1). The maximum-per-day bending moments are plotted on Gumbel probability paper, with Weibull Extreme Value statistical distributions fitted to the data in order to allow extrapolation to determine the 1 in 1000 year characteristic load effects. Figure 28 illustrates the extrapolation for scenarios B and E.

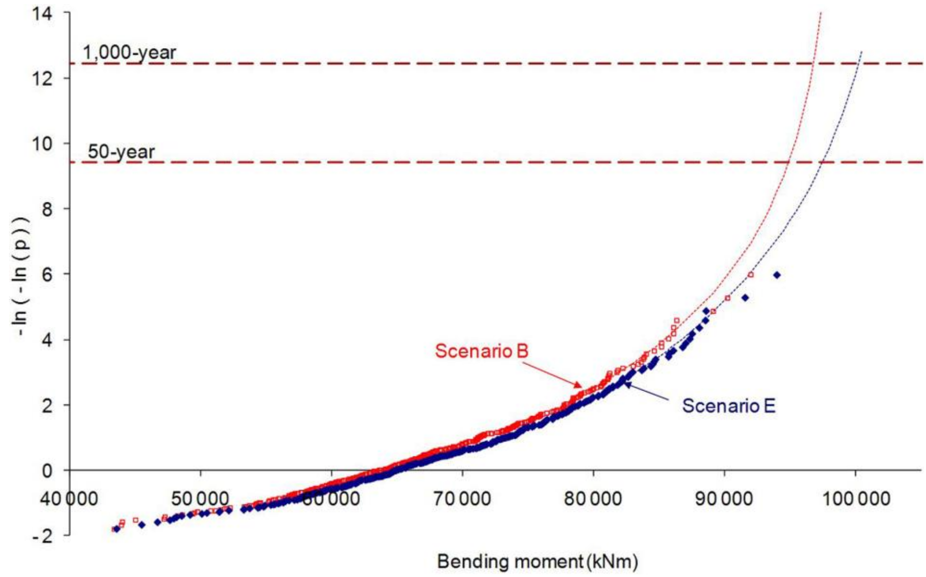


Figure 48: Maximum Per-Day Mid-Span Moment (Influence Line I1), 125 m Bridge

For this example, the characteristic maximum moment for a 1000-year return period is a little larger for Scenario E than it is for Scenario B, i.e., increasing all trucks near the current legal weight limit to the new proposed legal limit causes a modest increase in bending moment. However, there is a lot of variability inherent in the extrapolation and, more importantly, the result can be over-influenced by a small number of extremely heavy trucks. Based upon the results of the simulations and extrapolations performed, it was concluded that *no statistically significant difference was found between the characteristic load effects calculated from the five scenarios A-E*.

It was suggested that a better indication of the differences between the scenarios may therefore be obtained by examining the mean daily maximum load effects, rather than the extrapolated characteristic effects. It was seen that small increases were observed in the mean daily maximum load effects between scenario B and E, however these increases were in the region of a few percent and therefore were not deemed to be critical.

For the detailed analysis of the masonry arch bridges a large database of WIM data, recorded at five different sites across Europe was employed (the Netherlands, Poland, Czech Republic, Slovakia and Slovenia). In this detailed analysis, rather than using the factored tridem weight as defined for the 6-axle 46 t truck, it was deemed more statistically appropriate to determine the characteristic tridem weight for this class of vehicle, which was considered comparable with the BD21/01 tridem weight of 24 t (i.e. considered the approximate mean weight for a 40 t weight limit) factored by the partial factor prescribed in BD 21/01 of 1.9. An extreme value distribution was therefore fitted to the tridem weights of 6-axle trucks, facilitating calculation of the 1000 year characteristic tridem, whose effect was then compared to the 'factored' code tridems of BD 21/01.

It was shown that, for the entire set of masonry arch structures considered, the load effects induced by the calculated characteristic tridem were less than the factored tridem from BD21/01. It was concluded that the proposed increase in legal weight limits was unlikely to result in an exceedance of the code loading.

Pavement Damage

Based on an American field study in the 1950s, the 4th Power Law states that pavement damage is proportional to axle weight raised to the 4th power:

$$PWDF = \sum_{i=0}^{n} ESAL_i^4 \qquad \textit{(Eq. 2)}$$

where $PWDF$ = Pavement Wear Damage Factor, n = number of axles on the vehicle and $ESAL_i$ = Equivalent number of Standard Axles for axle i. This is calculated by dividing the weight of the axle being considered by a standard axle weight of 8 t (Therefore an axle of 8 t has an $ESAL$ = 1.0).

In order to give a rough estimate of the effect that a change in weight limits would have on pavement damage, a simple calculation was carried out using the 4th Power Law to calculate the level of pavement damage caused during the transportation of 1 million tonnes of freight either using 5-axle trucks at the regulation weight limits at the time (42 t derogation), or using 6-axle trucks at the newly proposed weight limit of 46 t.

Assuming an un-laden weight of 15 t for a 5-axle truck, each truck at the derogation weight limit of 42 t would be capable of transporting 27 t of freight on any given journey. Using these assumptions, 37,037 trucks would be required to transport 1 million tonnes of freight. Using WIM data, the standard axle weights for 42 t 5-axle trucks were identified and the corresponding $ESAL$s calculated. Applying the 4th power law (Eq. 1) resulted in a pavement wear damage factor of 264,673.

Carrying out a similar calculation for 6-axle 46 t trucks showed that only 33,333 trucks would be required to transport 1 million tonnes of freight and that the resulting $PWDF$ was 188 329, representing a 29% reduction in pavement damage when changing from 42 t 5-axle trucks to 46 t 6-axle ones. It was also shown that removing the derogation and reverting to the 40 t weight limit for 5-axle trucks would reduce pavement damage by 11%.

4.2.3 Conclusions

This study represents an example of how WIM data has been used in Ireland to carry out a detailed investigation into the implications of increasing the legal weight limits for trucks. The study examined the likely effects of the proposed changes on bridge safety by using influence lines to represent critical load effects for common bridge types in Ireland. In addition, an analysis of various types of single-span masonry arches was also carried out. Finally, using the 4th Power Law, a basic estimate of the effect on pavement damage was calculated.

Overall, it was concluded on the basis of the analysis performed that for the design and analysis of bridges in Ireland, on national and non-national routes, the proposed revision to vehicle weight limits would not render the currently employed codified load models as inappropriate. In addition, it was shown that a move towards 6-axle 46 t trucks over 5-axle 42 t trucks would lead to a reduction in pavement damage.

Following this study, the legal weight limits specified by Irish regulations have been revised, and the legal limit for 6-axle trucks has been increased from 44 t to 46 t. The weight limit for 5-axle trucks has not been changed to date but the intention is to revoke the 5-axle 42 t derogation in July 2016 when 5-axle trucks should revert to an upper weight limit of 40 t.

4.3 Using WIM data for bridge applications in Slovenia

Slovenian case study demonstrates the safety assessment procedure using real traffic data measured with WIM systems. It is focused on development of assessment loading schemes and on overview of benefits of using the measured structural parameters (influence lines, load distribution factors and dynamic amplification factors) to optimise structural analysis. Case study concludes with an example of safety assessment of old bridges including cost savings.

4.3.1 Slovenian bridges

The Slovenian national road network consists of 730 km of motorways and expressways and around 6 000 km of bi-directional main, regional and tourist roads. On these roads there are 2,300 bridges longer than 5 meters. Around 900 are on the motorways and expressways and are managed by the Motorway Company of the Republic of Slovenia (DARS) and the remaining 1,400 by the Slovenian Roads Agency (DRSI). The average age of Slovenian bridges is roughly 40 years, but:

- only 22 years on the motorways and expressways and
- almost 60 years on the other state roads, with 20% of them being older than 60 years and some dating back to the year 1800.

Knowing the age of bridges is a key to estimate their capacity as it implies the design code and loadings that were used at the time of construction. In Slovenia historically eight design codes were employed, starting with the Austro-Hungarian one from 1904. But only the last two, used for the last 40 years, account for the modern traffic loading. This is a minor issue for the motorway bridges which are mostly younger than 40 years, but is a serious problem for around 60% of bridges on the Slovenian state roads (orange columns in Figure 49) designed and constructed for traffic loading much lighter than today’s.

Moreover, many of these bridges are deteriorated, which further reduces their design capacity and many of them would have to be strengthened if assessed according to the Eurocode design code (2009). In order to avoid the unnecessary interventions, a safety assessment procedure was developed that accounts for realistic evaluation of the remaining capacity and implementation of realistic loading. Only the loading part is presented in this case study.

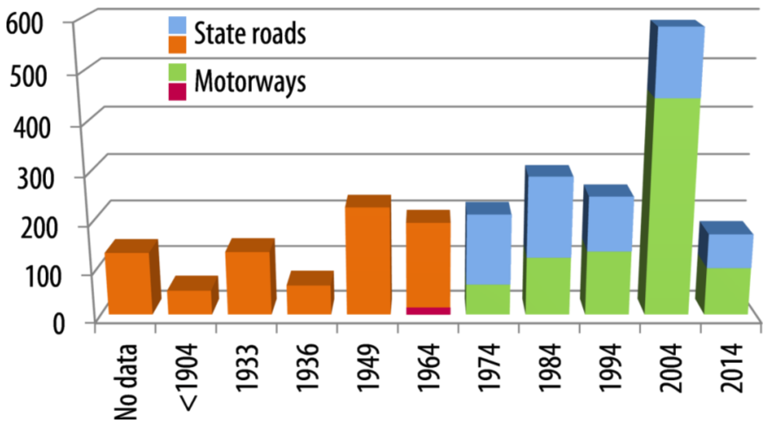


Figure 49: Capacity of Slovenian bridges

4.3.2 Safety assessment procedure for existing bridges

Here only the basic principle of safety assessment procedure for existing bridges is described. The objective of the safety analysis of an existing bridge is to show that the level of safety is sufficient under normal traffic conditions. Different approaches can be applied, from deterministic to full probabilistic. The Slovene recommendations express the level of safety in a deterministic way using the rating factor RF, derived from the original limit state formula:

$$RF = \frac{\Phi \times R_d - \gamma_G \times G_n}{\gamma_Q \times G_Q \times DAF} \qquad \textit{(Eq. 3)}$$

where:

R_d	is the bearing capacity of the assessed cross section,
Φ	is the capacity reduction factor,
G_n and G_Q	are the dead and live load effects,
γ_G and γ_Q	are the respective safety factors; as the dimension taken during inspection allow accurate evaluation of dead load γ_G is taken as 1.2; γ_Q is calculated according to the procedure from the recommendation and is typically taken as 1.7, and
DAF	is the Dynamic Amplification Factor.

To be safe, a bridge must exhibit RF greater than 1.

4.3.3 Development of assessment loading schemes for bridges using WIM data

When calibrating the traffic load model for bridge assessment, the goal was to find such loading scheme that would correspond to the Slovene traffic obtained with WIM and would at the same time provide rating factors RF as close to 1, regardless of the bridge span. In addition, it should resemble the loading scheme from the Eurocode LM1.

The WIM data considered in the development of bridge assessment loading schemes were collected on two WIM sites:

- on a motorway, from 5 months of measurements containing 307 360 vehicle records, and
- on a bi-directional main road, from 6 months of measurements containing 203 238 vehicle records.

To convert WIM data into load effects, similar assumptions were made as explained in section 4.2.2. Based on experience, three theoretical influence lines were considered as the relevant ones:

- for bending moment of a single simply-supported span (IL1 in Table 20),
- for shear (IL4/IL5 in Table 20), and
- for hogging moment over a support of multi-span bridges (IL9 in Table 20).

Loading schemes were developed for short to medium-span bridges where the current convolution method, see section 3.3.3, can be applied (the critical traffic load effect is a result of one heavy vehicle in each lane of traffic). This covers 54.3% of Slovene bridges on the motorways and 89.1% of bridges on the state roads. In reality, these figures are higher as the length of their influence lines (on longer bridges, between the expansion joints) not the physical length of the structure should be considered, but this information is not available in the central bridge database. Consequently, influence lines of 5, 15, 25, 35 and 45 meters were considered in the analysis. As an example, Figure 50 presents the calculated expected maximum bending moments for a 25 m simply supported span (influence line IL1) due to the motorway traffic.

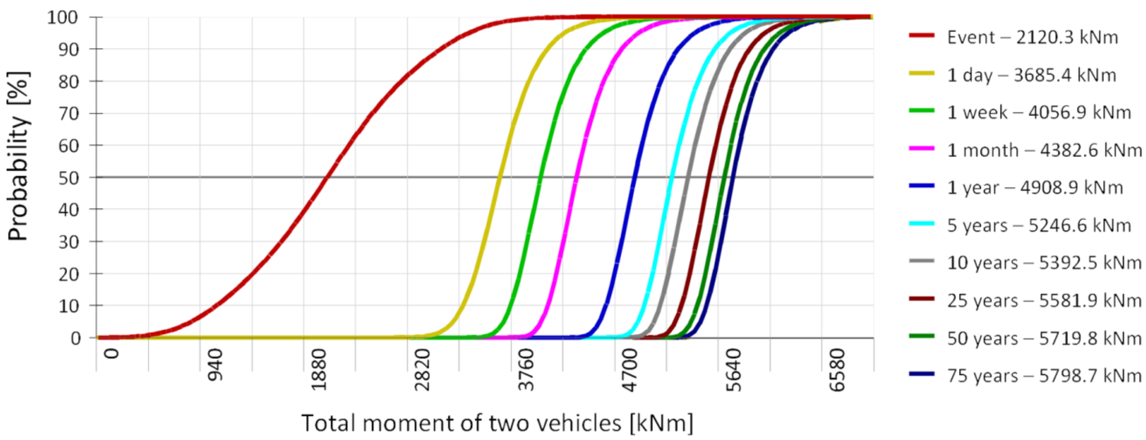


Figure 50: Expected mean bending moments on a 25-m simply supported span

As a result of the analysis, the assessment loading scheme EC_{RATING} was proposed. It is similar to Load Model 1 from the Eurocode 1 (2009), but distributes the high axle loads from 2 to 4 axles and applies slightly lighter uniform loading. In addition, safety of continuous structures over several spans is verified with the SLS-3 loading scheme with 2 heavily overloaded 4-axle rigid vehicles in each lane, Figure 51.

4.3.4 Other benefits of using WIM in assessment analysis of bridges

In Slovenia, until recently, load tests were compulsory for all new bridges longer than 15 meters, but not for existing deteriorated structures, which would benefit even more from knowing the true behaviour under loading. Many of them that carried traffic without any problems failed to pass the traditional safety check based on the design rules. The primary reasons were:

- reserves in carrying capacity, due to a different dimensions and quality of materials, compared to the design,
- conservative methods to calculate bridge resistance which do not take into account the hidden capacities, such as composite action between the slab and the beams, semi-rigid connections that were designed as flexible, boundary conditions etc.

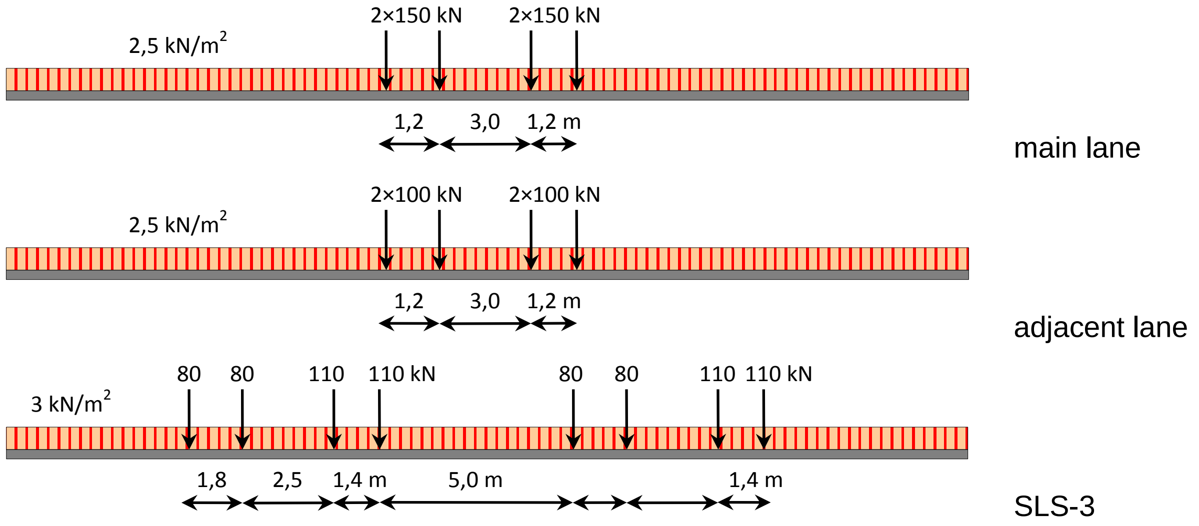


Figure 51: Bridge assessment loading schemes EC_{RATING} and SLS-3

With this in mind, the SiWIM® system was equipped with features for optimized bridge assessment. Initiated in the European research projects SAMARIS D30 (2006) and ARCHES D16 (2009) they took the advantage of SiWIM® measurements that derive the true influence lines, load distribution factors and dynamic amplification factors. Unlike the traditional diagnostic load tests, where these are obtained by the hired loaded vehicles, the *soft load test* or SLT uses the random traffic that traverses the bridge, which is considerably more time and cost-efficient. Furthermore, the users are not affected during measurements as the bridge *is left opened* for traffic. Results are used to calibrate the structural model which yields optimised assessment result and allows prescribing less severe rehabilitation measures and more efficient spending of the limited bridge management budgets.

Experimental influence lines

Influence lines transform loading into the load effects. Particularly on older and shorter bridges they differ considerably from the theoretical ones. The reasons are:

- bearings that do not keep to the theoretical behaviour,
- restricted movements of the expansion joints,
- soil pressure,
- lack of knowledge about the design details.

Influence lines are also the key for accurate B-WIM measurements (Žnidarič, Lavrič, & Kalin, 2010). Thus the SiWIM® always derives the influence lines from the measured data. Figure 52 shows an influence line averaged from 528 individual ones calculated from 10 hour traffic of all 2-axle trucks and 5-axle semi-trailers. The bridge was a 15-year old, 25-m long simply-supported structure with five prestressed beams spaced at 2.80 m from each other. The thinner lines depict 1 standard deviation interval of all influence line.

Figure 53 demonstrates the benefits of using SLT on the same bridge. The measured bending influence line substantially differentiates from a theoretical simply-supported one that would be considered on a bridge with bearings and expansion joints. When the boundary conditions of the structural model are adapted, the bending moments of the bridge reduce for 33%. This has a major impact on calculation of structural safety, particularly as on the older and shorter structures without proper bearings and expansion joints such savings can well exceed 100%.

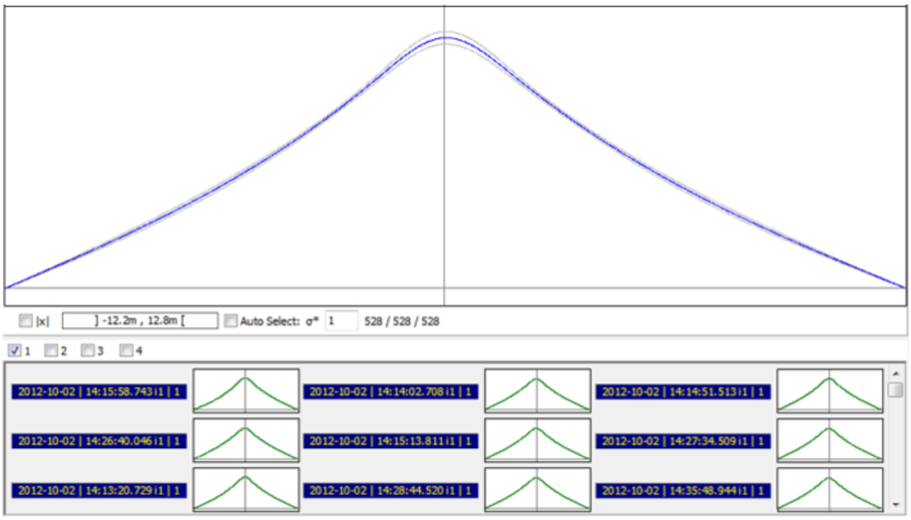


Figure 52: Influence line averaged from 10 hours of traffic - from SiWIM® software

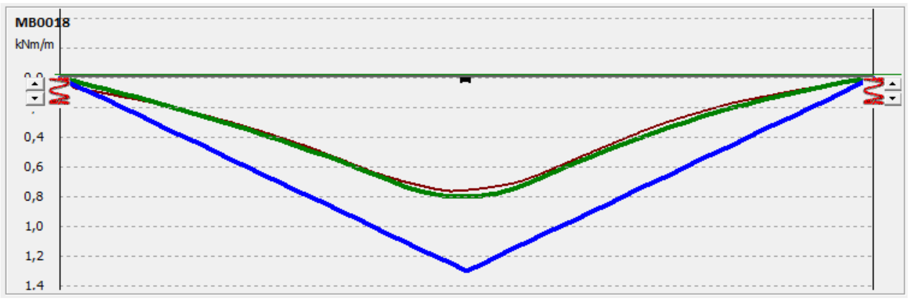


Figure 53: Comparison of theoretical (blue), measured (red) and experimental/model updated influence lines (green)

Load distribution factors

Knowing the true distribution of loading among the structural members can further improve the structural model. SiWIM® statistically evaluates the strains recorded on individual sensors (structural members), using information from thousands of vehicle loading events. Figure 54 shows how traffic loading is distributed over the beams of the bridge described above.

The main benefit of soft load testing is that it optimises the structural models at any complexity of structural model, from simple 1-D, as illustrated in Figures 53 and 54, to the most complex 3-D ones.

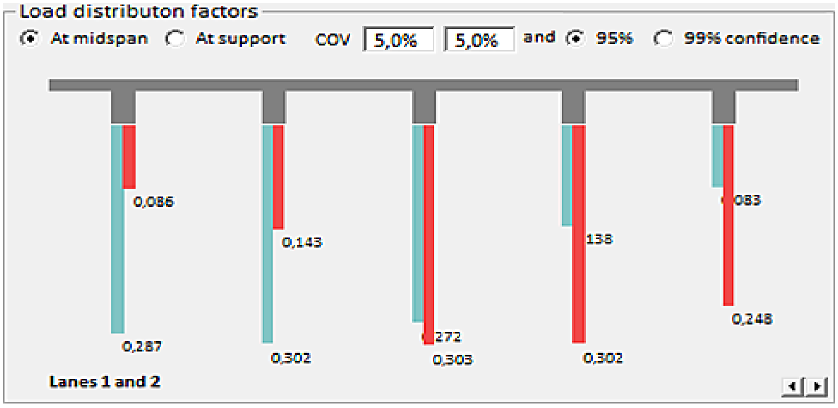


Figure 54: Measured and statistically evaluated load distribution factors for lanes 1 (blue) and 2 (red) obtained with a B-WIM system.

Dynamic loading

In the design codes, the dynamic traffic loading is generally considered in a conservative way. In other words, the dynamic amplification factor (DAF) used to multiply the static load effects with is much higher than in reality OBrien et. al. (2009). Recent studies in projects SAMARIS D30 (2006) and ARCHES D10 (2009) demonstrated that the dynamic amplification decreases as static loading increases. The reason is that the extreme loading events, which may include several heavy trucks with many axles, induce far smaller dynamic amplification than the lighter individual vehicles. This fact is extremely important for assessment of bridges.

As an example, the Figure 55 displays the DAF vs. strain function measured with the SiWIM® system on a 7-span bridge made of prefabricated reinforced concrete beams. The individual dots represent either the events with a single heavy vehicle (with the gross weight exceeding 35 kN) or multiple-presence events with one heavy and one light vehicle or with two heavy vehicles. The trend, as the traffic loads increase, is far closer to the values prescribed in the Danish bridge assessment code (DRD, 2004) than to those set in the bridge design codes.

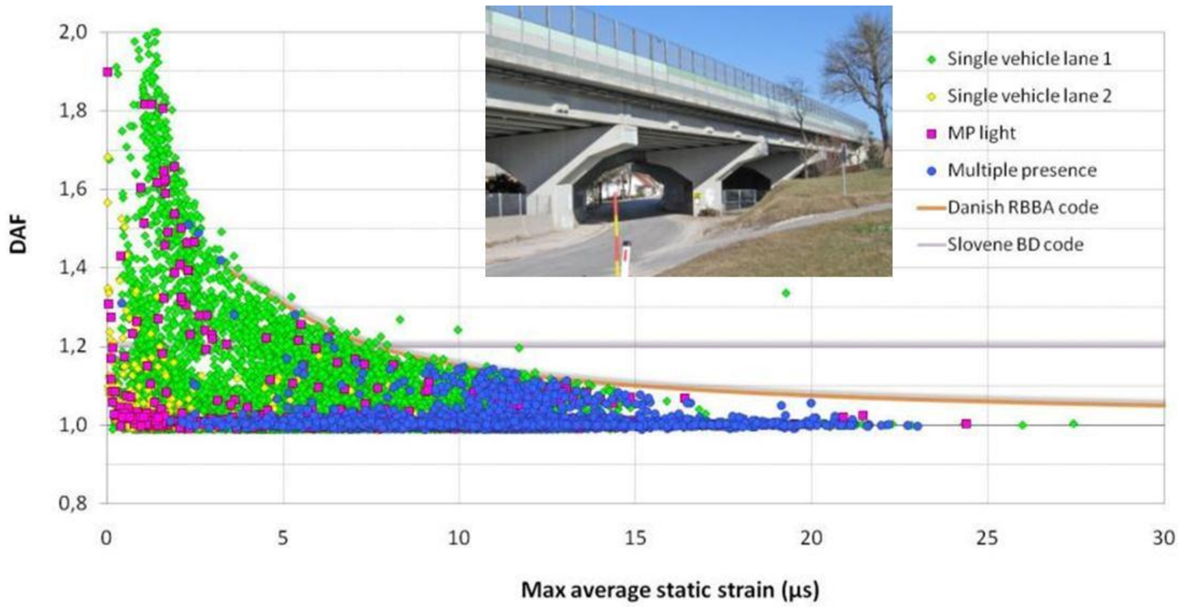


Figure 55: Dynamic amplification factors as a function of maximum measured static strain on a typical bridge (ARCHES D10, 2009)

In practice, this procedure requires reasonably long B-WIM measurements (a few months) and has in Slovenia not been employed yet on a bridge that needed structural reassessment. For cases with no B-WIM measurements the ARCHES project D10 (2009) suggested to take, based on bridge span and smoothness of the road surface, the DAF factors between 1.15 and 1.4. These values are implemented within the current Slovene recommendations (Žnidarič A. , 2010).

4.3.5 Safety Assessment of Old Bridges

Following the result of priority ranking a list of questionable bridges was compiled with respect to their structural safety. The primary reasons for inclusion on the list were:

- construction before the modern design codes with adequate loading,
- severe deterioration,
- no structural information in the archives, and
- verification for special (heavier) transports.

Over the last 12 years, structural safety of 253 underperforming bridges from this list was examined, of which 99 were for verification for special transports and 154 for the other three reasons. The rules and loading schemes explained above were applied in the analyses. The soft load tests were applied on the 99 structures that were assessed for the special transports. The reason was obvious, the considerably higher loading.

The remaining 154 bridges were at the early stage assessed with a low-level approach using only the thorough inspection and available information (their age, geometry, drawings and calculations from the archives, which for many old bridges did not even exist). Still, when combined with the capacity calculation methods and the assessment loading schemes described above, sufficient safety for the current traffic could have been shown for 118 of them, which corresponds to 77% of all cases. For the other 36 bridges the analysis was repeated. In most cases, it included the soft load tests to derive the true influence lines and load distribution factors, and in some cases also tests of materials and corrosion. Finally, for just 13 out of all 253 bridges sufficient structural safety could not have been confirmed, which equals to only <u>5.1% of all questionable cases</u>.

4.3.6 Cost savings

Applying a design code for assessment of underperformed bridges would, due to their age and associated insufficient capacity, disclose the majority of them as structurally deficient. Replacing them would cost, at an average price of 0.7 Million Euro per bridge, around 175 Million Euro. In the next step, without the soft load tests and detailed inspections with field tests, the costs for replacing the 36 remaining bridges not passing the level 1 assessment would cost around 26 Million Euro. Just strengthening would require roughly one third of these two amounts. In addition, postings and/or road closures during reconstructions would trigger substantial indirect expenses for users of these bridges, which, depending on the traffic density and duration of the road block, could cost *twice as much as the reconstruction works*. The cost to replace the remaining 13 critical bridges is well below 10 Million Euros.

Consequently, before applying strengthening or posting of heavy traffic, more elaborated assessment with soft load testing can be clearly recommended. In the case presented, only 5% of bridges needed posting and, subsequently, strengthening or replacement. At the same time, the postings prescribed were lower than they would be based on traditional analytical methods. For example, in some cases, the transport with 5-axle semitrailers could have been permitted and only gross weights of shorter rigid vehicles were limited. This allowed the local industries to continue operating without tangible disturbances.

5 Conclusions

Traffic loading is a critical variable which needs to be considered in the risk assessment of ageing bridge stock. Weigh-in-motion (WIM) systems provide the most accurate measurements of actual traffic loading. This document provides a state-of-the-art report on the availability of WIM data in the six countries funding this CEDR call (Denmark, Ireland, Netherlands, Slovenia, UK, Germany), plus France. Guidelines for collecting quality WIM data are provided and examples are given of good practice of using WIM data for bridge applications on how NRAs can collect and use it.

The seven countries were analysed with respect to WIM locations, technologies, data and applications. Results show that all countries collect WIM data on primary roads. Mostly, permanent long-term measurements are performed which provide a large amount of WIM data. All countries use pavement WIM systems, with the exception of Slovenia, which is using portable bridge WIM systems. For the (re)calibration and determination of the accuracy of the WIM systems different procedure are used. WIM data in all countries is available in vehicle-by-vehicle format, which is required for bridge applications. Precision of the reported time stamps is at least 0.1 s, with exception of UK and Denmark where information is available to the nearest second. WIM is used for different purposes, but, according to available information, currently only a few countries systematically use WIM data for bridge applications.

Chapter 3 provides an overview of the existing COST 323 guidelines for collecting good quality WIM data. It also presents guidelines for assuring the quality of WIM data and for cleaning erroneous records. Examples of good practice of using WIM data for bridge applications are also given along with a summary of the US recommendations on using WIM data for bridge design, the only available document of the kind.

Three case studies demonstrate the importance of using WIM data for bridge applications.

The case of the Millau Bridge gives an example for long-span bridges where the codes do not apply. Results show that the extreme values obtained for the effects calculated with application of the WIM data are 65% smaller than the extreme effects obtained with application of the regulatory load. It highlights the importance of WIM data in order to assess precisely the effects induced by traffic. This is not only the case in the design phase of a bridge, but also during assessment of existing bridges. The Millau case also shows the importance of using enough WIM data in order to have an estimation of the worst case (and thus the stability of the results).

The second case study shows how WIM data has been used in Ireland to carry out a detailed investigation into the implications of increasing the legal weight limits for trucks in Ireland. On the basis of the analysis it was concluded that for the design and analysis of bridges in Ireland, on national and non-national routes, the proposed revision to vehicle weight limits would not render the currently employed codified load models as inappropriate. Following this study, the legal weight limits specified by Irish regulations have been revised, and the legal limit for 6-axle trucks has been increased from 44 t to 46 t. The weight limit for 5-axle trucks has not been changed to date but the intention is to revoke the 5-axle 42 t derogation in July 2016 when 5-axle trucks should revert to an upper weight limit of 40 t.

The third case study demonstrates the procedure for development of assessment loading schemes to represent the real traffic measured with WIM systems in Slovenia. It also shows the benefits of using the measured structural parameters (influence lines, load distribution factors and dynamic amplification factors) to optimise structural analysis. Finally, great financial savings have been demonstrated after applying the proposed methods.

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