Monitoring railway traffic loads using Bridge Weight-in-Motion

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Preface

The work presented in this thesis has been carried out at the division of Structural Design and Bridges, Department of Civil and Architectural Engineering, KTH University. I would like to thank Pär Olofsson at the Swedish railway administration (Banverket) and the European sixth framework programme, Sustainable Bridges, for financing the research in this thesis.

I want to express my gratitude to my supervisor Associate Professor Raid Karoumi, who has gone above and beyond his obligations at every step of this project. This thesis would not have been written without him. I would also like to thank my Professor Håkan Sundquist, the field technicians Claes Kullberg and Stefan Trillkott, my many helpful and knowledgeable associates including Richard Malm, Johan Wiberg, Mahir Ülker, Andreas Andersson, Merit Enckell and Hans-Åke Mattsson. I would also like to thank Anna Tannenberg and Johan Wiberg for proofreading this thesis.

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Abstract

While there has been much research into the field of Bridge Weigh-in-Motion (B-WIM), this research has focused on road traffic. Because of the differences in traffic properties, it is not applicable to B-WIM for railway traffic without some modifications.

The research contributions accounted for in this licentiate thesis is a set of algorithms for performing B-WIM calculations on railway traffic. It has been implemented in the MATLAB language as a toolbox of functions, tailored to easily performing B-WIM calculations. This toolbox, called Twim, is described in detail in the appendices of this thesis.

This thesis describes the algorithms of the B-WIM system. That includes algorithms for determining the speed of a train, an algorithm for determining the influence line of a bridge at a sensor position from the signal of a passing train, and a simple algorithm for locomotive identification.

Lastly, this thesis outlines some of the results obtained from measurements using the system, and investigates dynamic effects as well as changes in bridge properties over time.

As a result of the research conducted in this thesis, the following conclusions can be drawn:

- The algorithms described in this thesis are suitable for B-WIM on railway traffic.
- Different types of bridges can be instrumented for B-WIM by measuring transverse strain instead of longitudinal strain, since the former gives a more local traffic effect. Longer bridge span and lower damping ratio do however significantly reduce the accuracy of the system.
- Long term effects such as changes in bridge properties due to temperature changes could not be detected during the seven month measurement period.
- High vertical bridge deck acceleration levels are often detected, but they are found to be the result of wheel defects rather than resonance phenomenons.
- Wheel defects significantly reduce the accuracy of the B-WIM system.

Keywords: Bridges, Weigh-in-Motion, B-WIM, Dynamics, Traffic load, Railways, Acceleration, Measurements.

Sammanfattning

Mycket forskning har utförts på brobaserat vägande av fordon i rörelse (Bridge Weigh-In-Motion, B-WIM). Denna forskning har varit fokuserad på fordonstrafik och är inte applicerbar på järnvägstrafik utan vissa ändringar.

Denna licentiatavhandling beskriver arbetet som kulminerat i en uppsättning algoritmer för att utföra B-WIM-beräkningar på järnvägstrafik. Algoritmerna har implementerats i form av en uppsättning funktioner i programmeringsspråket MATLAB. Dessa funktioner, kallade Twim, är beskrivna i detalj i appendix till denna avhandling.

Denna avhandling beskriver de algoritmer som används av B-WIM systemet. Detta inkluderar metoder för att bestämma hastigheten av passerande tåg, en metod för beräkning av influenslinjen av en bro vid en given sensorposition utifrån en mätsignal av en tågpassage, samt även en metod för att utföra lokomotividentifiering.

Slutligen analyseras en del av de mätdata som har inhämtats av systemet, och dynamiska effekter samt förändringar i broegenskaper över tiden undersöks.

Forskningen utförd i denna avhandling leder till följande slutsatser:

- Algoritmerna som beskrivs i denna avhandling är lämpliga för B-WIM av järnvägstrafik.
- Olika sorters broar kan instrumenteras för B-WIM genom att mäta transversell spänning istället för longitudinell spänning, eftersom den förra ger en mer lokal trafikeffekt. Längre brospann och lägre dämpning minskar dock noggrannheten i systemet signifikant.
- Långtidseffekter som ändringar i broegenskap på grund av temperatur kunde inte visas under den de sju månader mätningarna pågått.
- Hög vertikal brodäcksacceleration påträffades ofta, men kunde visas bero på hjuldefekter, inte resonansfenomen.
- Hjuldefekter påverkar noggrannheten i B-WIM systemet signifikant.

Contents

Preface iii

Abstract v

Sammanfattning vii

Outline of Thesis xi

Contribution of Thesis xiii

1 Introduction 1

1.1 Background 1

1.1.1 Monitoring of railway traffic 1

1.1.2 Uses for B-WIM 2

1.2 Aim and scope 4

2 Literature review 5

2.1 Pavement based Weigh-in-Motion systems for road traffic 5

2.2 Bridge based Weigh-in-Motion systems for road traffic 6

2.2.1 Moses algorithm 8

2.2.2 CULWAY 9

2.2.3 SiWIM 9

2.2.4 Further B-WIM improvements 9

2.2.5 Axle detection methods 10

2.3 Weigh-in-Motion for railways 10

2.3.1 WILD 11

2.3.2 GOTCHA 11

3 Overview of the instrumented bridges and the toolbox 13

3.1 Instrumented bridges 13

3.2 Toolbox overview 14

4 Additional results 19

4.1 Identified train passages 19

4.2 Calibration 20

4.3 Overall trends 22

4.4 Temperature's influence on bridge properties 24

4.5 Accuracy of B-WIM results 24

5 Conclusions and future research 27

5.1 Discussion of the outlined results 27

5.1.1 Dynamic bridge behavior 27

5.1.2 Long term trends 28

5.1.3 Accuracy of the B-WIM algorithm 28

5.2 Suggested future work 28

5.2.1 Further developments of the described methods 28

5.2.2 Studying bridge behavior 29

Bibliography 31

Appendices 33

Outline of thesis

Chapter 2 is a review of previous WIM research. It describes previous research in pavement based WIM using sensors embedded in the tarmac of the road. The development of bridge based WIM, from the initial research done by Moses to later research projects such as CULWAY is described. More recent projects, such as the WAVE project and the resulting SiWIM system are also described. Finally, chapter 2 also describes previous studies on WIM specifically for railways, such as WILD and GOTCHA.

Chapter 3 gives an overview of the tools developed during the work on this thesis, as well as the bridges on which these tools have been tested.

Chapter 4 presents results from additional measurements performed after the submission of the last article included in this thesis.

The final chapter, chapter 5, discusses the results from chapter 4, as well as the results from the articles presented in this thesis, and outlines the implications of these results. This chapter also discusses potential future research possibilities.

The rest of this thesis is a collection of papers, included as Appendix A–C, by the author on the subject of B-WIM. The papers included in this thesis are:

A Karoumi, R., Wiberg, J., Liljencrantz, A. (July 2005). Monitoring traffic loads and dynamic effects using an instrumented railway bridge. *Engineering Structures*, 27:1813-1819.

  This article gives an in depth description of the instrumentation used to perform the measurements in the later articles, it also describes one of the test bridges in detail.

B Liljencrantz, A., Karoumi, R., Olofsson, P. (2007). Implementing Bridge Weigh-In-Motion for railway traffic. *Computers & Structures* 85:80-88.

  This article gives a detailed description of the algorithms developed to perform B-WIM on railways, and includes results from performing B-WIM measuring on the Årstaberg bridge.

C Liljencrantz, A., Karoumi, R., Twim, (Submitted for publication) A MATLAB toolbox for real-time evaluation and monitoring of traffic loads on railway bridges.

This article describes how to use the algorithms described in the previous article. Specifically, it describes a MATLAB toolbox developed to make such an analysis as simple as possible. This article also contains results from measurements on the Skidträsk bridge.

Contribution of thesis

Though there has been much research on performing Bridge Weigh-In-Motion calculations on road traffic, and working commercial systems for this purpose have existed for several years, no attention has been given to the possibility of performing such calculations on railway traffic. While many of the basic ideas apply equally well to both types of traffic, there are some inherent new difficulties when handling railway traffic that need to be addressed.

The work described by this thesis has led to the creation of a complete B-WIM system, specifically designed for railway traffic. The system has been tested on two bridges, and the results have been used to analyze the traffic crossing the bridge, the dynamic effects from passing traffic on the bridge as well as the properties of the bridge itself.

Chapter 1

Introduction

1.1 Background

Research in the area of bridge design has traditionally been focused on studying bridge properties like material strength. Much less is known about actual traffic loads and their effects on bridges. The correctness of the traffic loads, current safety factors and dynamic amplification factors used today by bridge engineers for design and assessment of bridges has been questioned (James, 2003).

The DIVINE project asserted that significant cost reductions are possible in infrastructure maintenance by changing the way the current road and railroad infrastructure is used (Directorate for science, technology and industry, 1998). Within the bridge engineering community, there is today a considerable interest in the problem of measuring actual traffic loads and their dynamic effects on bridges (Wong, 2006; O'Brien et al., 2003; SB, 2007).

In Sweden, several bridges have recently been instrumented using strain transducers placed on the soffit or embedded in the bridge deck, as described in Appendix A. This relatively inexpensive instrumentation makes it possible to determine vehicle characteristics such as speed, axle distances, and static axle loads. Systems for performing such weighing operations on moving vehicles are usually referred to as Weigh-in-Motion (WIM) systems. WIM systems that use an instrumented bridge to obtain information for WIM calculations are usually called Bridge Weigh-in-Motion (B-WIM) systems (Quilligan et al., 2002; Quilligan, 2003).

1.1.1 Monitoring of railway traffic

Almost all research in the field of WIM has been performed on road traffic. The reason for this is most probably that because of the unregulated nature of road traffic, measuring is the only way to find out how much traffic is actually moving over a specific site. Railways, in comparison, are much more closely regulated. It is not uncommon for railway owners to only have a single customer for each stretch of railway.

Despite this, railway owners do not have perfect information about the traffic flow on their lines. Some degree of overloading might be present when dealing with freight traffic, and railway owners that lease out the use of their tracks do not always have perfect data on the amount of train traffic.

For these reasons, traffic data derived from B-WIM calculations may prove useful to railway track owners.

Another reason for performing B-WIM instrumentation on railway bridges is to investigate the dynamic properties of bridges. Increased vertical acceleration of the bridge deck is a problem for many bridges as train speeds increase. A high level of vertical acceleration leads to excessive vibration of the bridge deck, which can cause ballast displacement. Ballast displacement may in turn cause degradation of support to tracks and lead to major additional maintenance costs (Norris et al., 2003). In extreme cases, vertical acceleration may also cause derailing. For this reason, the UIC (2003) design requirements for rail bridges state that the maximum deck acceleration may not exceed 0.35 g for frequencies up to 20 Hz. Similarly Banverket (2004), the Swedish railway administration design code for new bridges state that for ballasted bridges and frequencies below 30 Hz, the vertical acceleration for the bridge beam may not exceed $3.5\,\mathrm{m/s^2}$. For unballasted bridges, the maximum acceleration permitted is $5.0\,\mathrm{m/s^2}$.

These acceptance criteria where originally obtained from shake table testing. Norris et al. (2003) describe such testing, involving sinusoidal testing of UK ballast in the frequency range of 5 to 50 Hz and vertical acceleration levels from 0.25 to 2 g. These tests found that some decks are susceptible to resonance, causing higher degradation due to long acceleration waves at a multiple of the train forcing frequency or low damping. For such bridges, acceleration levels of 0.5 g may damage the bridge. However, the study also found that bridges with a high damping will exhibit stochastic vibrations and local effects which will greatly reduce ballast displacement, and for such bridges, accelerations of 1.0 g can actually be accepted without harm to the ballast.

1.1.2 Uses for B-WIM

A B-WIM system can be used not only for assessing the traffic passing over the bridge, but also to study the response and behavior of the bridge itself. Some of the use cases for a B-WIM system are presented below.

Obtaining information on actual traffic loads

The most obvious use of B-WIM is to obtain unbiased information about actual traffic loads. Such data is critical for calibrating traffic load models, checking road/rail safety requirements of existing bridges, and for the assessment of existing bridges by using site specific traffic load models.

O'Brien et al. (2003) collected traffic weight, volume statistics and direct strain measurements. By extrapolating the traffic loads, they could determine the characteristic strain in the bridge beam, giving them an accurate measure of traffic load effects. The technique was shown to be effective, but sensitive to the period of simulation time. The conclusion that can be drawn is that to attain a characteristic strain with a high accuracy, one needs to use long measuring periods, preferably using permanent instrumentation.

Detecting overloaded vehicles

There is considerable interest in using WIM techniques for law enforcement purposes, mostly for checking that lorries travelling over road bridges are not overloaded. (Stanczyk and Marchadour, 2005; O'Brien and Znidaric, 2001) There is also much interest from owners of railway in detecting wheel flats. Wheel flats can cause a great deal of damage to both the train itself and the infrastructure if undetected. This thesis shows that B-WIM instrumentation can be used to detect such defects.

Measuring dynamic response

The dynamic amplification factor of a bridge can be determined using simulations based on measured speeds, static axle loads and distances, and comparing the results of these simulations to actual measured dynamic response curves.

As an alternative, it may be possible to obtain the dynamic amplification factor by low pass filtering a signal to remove all dynamic effects, and comparing this filtered signal to the original, unfiltered signal.

Measure how bridge properties change over time

Bridge properties change over time and are caused by many factors, including seasonal changes due to the freezing cycle, the effects of bridge repairs and long term degradation due to concrete cracking and other aging effects. If such changes alter the bridge influence line or other properties that can be detected using a B-WIM system, it would be possible to estimate the overall state of the bridge using B-WIM methods.

Current bridge damage detection methods are mainly visual. Such methods are not only time consuming and expensive, they can not be used to detect damages that are internal to the structure. The instrumentation of a bridge has the potential to be used as a general structure health monitoring system. By monitoring changes in influence line characteristics such as area and curvature and detecting changes in these characteristics over time, it is hoped that global structure damage can be detected at an early stage (Getachew, 2004).

B-WIM traffic data including vehicle loads and traffic density can be combined with degradation data to estimate how traffic density affects the aging of a bridge.

1.2 Aim and scope

This thesis aims to investigate the possibilities of using a B-WIM system on railway bridges. Some of the specific goals that this thesis tries to achieve include:

- Analyze WIM algorithms constructed for use with road traffic and check their suitability for use as railway-based WIM.
- Implement a set of algorithms for railway-based B-WIM.
- Implement a toolkit containing tools for B-WIM calculations.
- Evaluate the algorithms using large amounts of real world traffic on two real bridges.
- Study bridge dynamic behavior (vertical bridge deck acceleration) using B-WIM methods.

Chapter 2

Literature review

In this chapter, an overview of the current state of the art of Weigh-in-Motion will be given. Different methods, including methods specific to pavement traffic as well as bridge based WIM methods are presented. The chapter finishes with a description of research on WIM for railways.

The idea of using B-WIM techniques for performing measurements on railway bridges is new. It is believed that the author is the first to study and implement such a system. However, various WIM techniques have been in use for several decades when measuring road traffic and most of the bridge based techniques can be transferred to apply to railways. Therefore, B-WIM for railways has a rich history of road based B-WIM research to draw from.

2.1 Pavement based Weigh-in-Motion systems for road traffic

Traditionally, traffic monitoring of heavy vehicles was performed by manually counting vehicles and by utilizing static weigh stations (Quilligan, 2003). Using this method in a way that produces reasonably unbiased, accurate and statistically relevant data is both expensive and hard. For this reason, different types of semi-automatic or completely automatic WIM have been of great interest.

Early WIM methods utilized scales or pressure sensors embedded into the road pavement. Unless the measured vehicles travel at low speed, this type of WIM has proved to be too inaccurate to provide results that are usable for most situations. There has been great interest in increasing the accuracy of WIM methods, and to make it possible to perform WIM on vehicles travelling at full speed. Such a system has many potential uses, including:

- Law enforcement purposes. Studies have shown that approximately 20 % of the pavement maintenance costs in the Netherlands are due to overloaded trucks (Henny, 1998).

- Improved road safety. As overweight trucks have decreased operational performance, they can be a safety hazard.
- Improved understanding of pavement damage (Caprez, 1998; Raab et al., 2005).

There are several problems with the early WIM systems that make them unsuitable for high speed use. These problems are mostly centered around dynamic effects. A vehicle moving at normal highway speeds has a significant dynamic behavior caused by a large number of components, mostly in the vehicle suspension. The road itself is also susceptible to dynamic effects. This situation is made worse by the fact that pavement sensors induce additional dynamic effects, both because they make the pavement less smooth, and because drivers, especially those in overweight vehicles, tend to avoid them.

Many improvements to pavement WIM systems have been devised. One such method is using a very large array of sensors, spaced at distances designed to maximize the frequency information in the results, leading to a better estimate of vehicle weight. This still has the drawback that the sensors themselves induce more dynamic behavior, making the weighing process more difficult. Another method, employed by Raab et al. (2005), is to not place the sensors in the pavement, but in the ground below the pavement. This has the advantage of not introducing any additional dynamic effects on the vehicle, and also means that measurements are performed over a slightly longer period of time, as the pressure of an axle on the road is somewhat spread out sideways. This second method solves many of the classical pavement WIM problems, but the effects on the weight distribution from temperature changes causes new complications, and it may prove impossible to retrofit an existing road with such sensors.

2.2 Bridge based Weigh-in-Motion systems for road traffic

Bridge Weigh-in-Motion (B-WIM) is a type of WIM that utilizes a bridge to perform the measurements, as seen in figure 2.1. This can be compared to the use of sensors embedded into the road below the pavement described in the previous section. This method has several advantages:

- The main problem in WIM that can be lessened in B-WIM is that of dynamic effects. As described above, WIM systems are notoriously sensitive to dynamic effects because the measurements are performed over a very short period of time. A B-WIM configuration usually is constructed to measure a vehicle over at least one bridge span, which is enough to average out dynamic effects for nearly any type of vehicle.

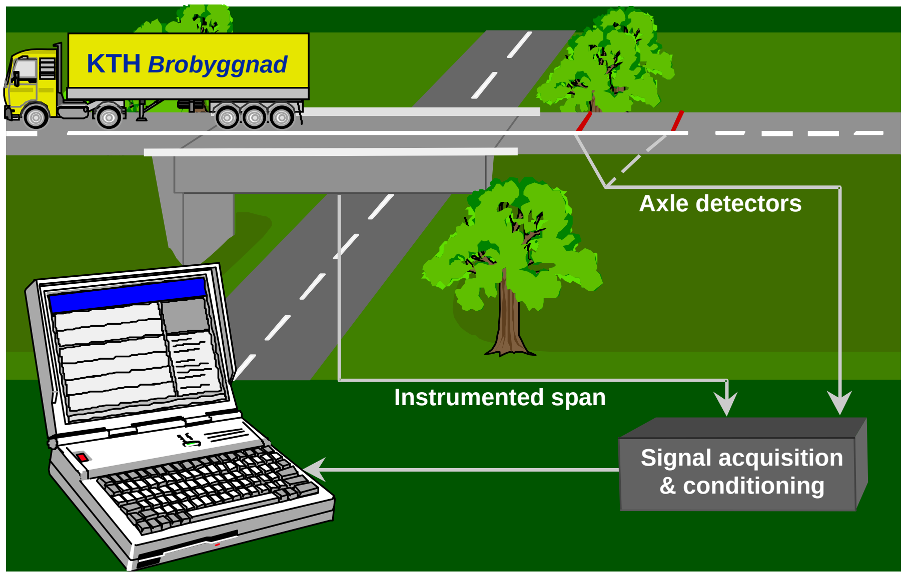

Figure 2.1 shows the elements of a B-WIM system for road traffic. Redrawn from WAVE final report.

- Instrumenting a bridge also allows you to collect data on the bridge itself. Such measurements can provide valuable information on bridge behaviour, which, depending on the situation, can mean decreased maintenance costs, improved safety and longer bridge lifetime.
- A bridge can often be retrofitted with B-WIM sensors without disturbing traffic. Pavement and track based WIM require one to halt traffic during installation, which can be prohibitively costly, especially when using multiple sensors or deeply embedded sensors.
- The instrumentation is invisible to vehicles being measured, making it harder for overloaded vehichles to purposefully avoid weighing.
- B-WIM systems can often be made portable. That makes it possible to move the weighing stations and thus get information on traffic passing over several bridges with a single system.

Recent research in Europe on the development of WIM has been largely financed within the COST323 and WAVE projects. COST323 was an intergovernmental cooperation framework for scientific and technical research. It was initiated by the Forum of European Highway Research Laboratories and formed a part of the COST-Transport program. WAVE (Weighing-in-Motion on Axles and Vehicles for Europe) was a research and development project of the fourth Framework programme (Transport) to further the knowledge on various types of WIM in Europe. The two and a half year long project ended in 1999. The project resulted in new theories, models, algorithms and procedures, as well as several field tests to evaluate these developments. Possibly the most significant result of WAVE was the development of the SiWIM B-WIM methods used commercially by the Slovenian ZAG institute.

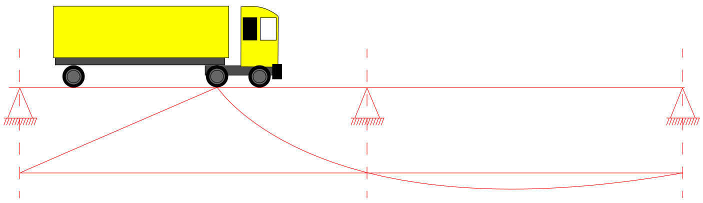

Figure 2.2 illustrates the influence line for beding moment at the point under the second axle of the truck passing over a bridge.

To be able to compare the performance of different WIM systems, it is necessary to define a common accuracy criteria. The COST323 management committee prepared a specification that gives an indication both of what accuracy might be achievable from sites with specific characteristics and what accuracy might be acceptable for various needs. This specification divides WIM systems into six accuracy classes, A(5), B+(7), B(10), C(15), D+(20), D(25) and E. A(5) systems are considered accurate enough for legal purposes like enforcement of weight limits, B and C systems are suitable for infrastructure design, D and E systems are suitable for collecting statistical traffic data (Quilligan, 2003).

2.2.1 Moses algorithm

Almost all proposed B-WIM algorithms rely on variations of an observation know as Moses algorithm. Moses (1979) algorithm deals with a bridge property known as the influence line. An influence line for a given function, such as a reaction, axial force, shear force, or bending moment, is a graph that shows the variation of that function for a given point on a structure due to the application of a unit load at any point on the structure (Fanous, 2007). Figure 2.2 shows an illustration of an influence line.

A load moving over a structure such as a bridge will effect a sensor placed on the bridge in proportion to the product of the value of the influence line at the loads momentary position and the axle load magnitude. This implies that if the locations of a vehicle's axles, the load of each axle and the influence line of the bridge at the position of a sensor placed on the bridge are all known, the reading from the sensor can be theoretically calculated with a very high degree of precision. When performing B-WIM calculations, this operation is instead done in reverse, the goal is to find the axle distances and axle loads that correctly approximate the given sensor readings. Because of dynamic effects, the true reading from a sensor will vary with each sample, but as a B-WIM system allows one to perform many measurements during the whole passage of a vehicle over a bridge, which is a relatively long period of time, the influence of dynamic effects on the influence line can be minimized.

The system used by Moses (1979) consisted of a button box, tape switches, strain gauges and an instrumented van. It produced results with standard errors of less than 10 %. Further improvements to the system reduced this error to roughly 6 %, but the algorithm proved unsuccessful at detecting tandem axles.

2.2.2 CULWAY

During the 1980's, a large amount of B-WIM related work was performed in Australia by Peters (1986). The AXWAY and CULWAY systems did not use Moses algorithm, instead they used the assumption that the area under the influence line is proportional to the gross vehicle weight, an assumption which is true if all vehicles travel at the same speed. The system was hampered by the slow computers of the time, which did not allow for real-time processing, and instead required manned operation.

2.2.3 SiWIM

Within the WAVE program a commercial B-WIM system called SiWIM was developed at ZAG in Ljubljana (O'Brien and Znidaric, 2001; Znidaric et al., 2005). While some early tests by Quilligan (2003) showed many miss-matches caused by the lack of temperature correction, later studies featuring temperature compensation have been found to give very accurate results. The SiWIM program has also been extended to handle many different types of bridges, different types of influence lines and instrumentation without axle detectors (Znidaric et al., 2005).

2.2.4 Further B-WIM improvements

Quilligan (2003) has implemented several improvements to existing B-WIM algorithms. These include:

- The use of a 2D influence line, i.e. an influence surface. This is beneficial since in reality the influence line for many bridge types varies depending on the transverse position of the vehicle on the bridge. According to Quilligans tests, these variations are in the order of 5 % for many bridges.
- A highly accurate method for direct or automated calculation of the influence line of a bridge through a small set of measured test runs (O'Brien et al., 2006), called the Matrix method.
- Improved handling of multi-vehicle events. It was shown that using a 2D model gave a large increase in the robustness of the detection code.

Using these techniques, Quilligan was able to attain the A(5) accuracy class for one of his trial WIM setups, which is the highest accuracy class available.

2.2.5 Axle detection methods

One of the problems WIM-algorithms face is that of axle detection. Having exact knowledge of the speed and position of each axle of a vehicle travelling over a bridge is critical when estimating the load of the axles. In traditional road-WIM systems, at least two sensors, usually in the form of pneumatic tubes, are placed on the pavement, as shown in figure 2.1. This method has many drawbacks. The installation of the sensor requires one to halt traffic, the installation itself is difficult, and because of the significant wear-and-tear of the system, the results are unreliable and maintenance costs are high (Quilligan, 2003; O'Brien and Znidaric, 2001). With railway WIM, pneumatic rubber tubes are obviously impossible to use, since the train wheels would destroy the tubes.

Because of the drawbacks associated with pneumatic tubes, it has been suggested that a system for axle detection without any pavement or track sensors would be desirable. Originally such systems where referred to as 'Free-of-Axle-Detector' (FAD), but because of initial confusion regarding the meaning of the name, they are now usually referred to as 'Nothing-On-Road' (NOR).

For B-WIM applications, several such algorithms have been suggested, all using the sensor output from the strain transducers of the bridge to detect the individual axles of a vehicle. This is not a trivial process, since the very long measurement periods in B-WIM means that multiple axles will influence the sensor at the same time, giving a 'smeared' result.

Znidaric et al. (2005) has designed a NOR system for bridges, which uses advanced filtering techniques to give sharper peaks that result in separate axles. Dunne et al. (2005) use wavelet signal analysis to achieve the same type of results. This thesis will propose a third such algorithm, based on pattern matching. All these techniques exploit the same knowledge about the system, namely that one knows roughly what the signal from a single axle should be. Performing axle detection then becomes the process of finding the distribution of axles that most closely matches the original input.

2.3 Weigh-in-Motion for railways

The previous discussion of WIM has been centered on WIM for road traffic. But many of the reasons why WIM is desirable for road traffic are also true for railway traffic. Because railways do not have pavements, the pavement-based WIM is not suitable for railway purposes. B-WIM, however, has no such problems. There are however several important differences between B-WIM on railways and B-WIM for regular road traffic.

- Trains are much longer, and have many more axles than a road vehicle. This means that a single detected vehicle may contain hundreds of axles. In many cases, the acceleration of the train during the passage needs to be taken into account.

- Trains run on tracks. This means that the problems associated with differences in sensor sensitivity based on where in the lane a vehicle is driving do not exist. According to Quilligan (2003), this can be a large source of inaccuracy in road WIM.
- There are no problems with identifying separate trains, since two trains never drive so closely to each other as to be confused with a single entity, and the strain originating from trains on different tracks can usually be separated from each other.
- There are only a small number of locomotive types, and electric locomotives usually do not vary in weight, which opens up the potential for auto calibration, i.e. the automatic recalculation of influence lines.

2.3.1 WILD

The WILD (Wheel Impact Load Detector) system is a track-based wheel defect detection system designed for railways using rail-mounted strain gauges. A track instrumented with strain gauges for the WILD system can be seen in figure 2.3. WILD can be used to:

- Check for wheel impacts
- Perform Weigh-in-Motion
- Test rail stress
- Check for skewed tracks
- Measure ambient conditions, like temperature, wind direction, etc.

As can be seen, the WILD system has many potential uses, but while it is useful for detecting wheel- and track defects, it is generally not accurate enough for WIM purposes. A more detailed analysis of the WILD system can be found in James (2003) and at http://www.salientsystems.com/.

2.3.2 GOTCHA

Graaf et al. (2005) have developed GOTCHA, a system for railway WIM based on glass fibre sensors mounted underneath the rail. A track instrumented with GOTCHA fibre sensors can be seen in figure 2.4. The sensors are used to convert the vertical deflection of the rails due to the passing wheel into a change in the optical signal, which is recorded and analyzed. These optical sensors have a very flat

Figure 2.3 shows a typical WILD site with the wiring and the strain gauges welded onto the rails. Copied from Salient's homepage with permission.

Figure 2.4 shows a railway track equipped with GOTCHA fiber optical sensors.

frequency response up to 1 kHz, and this in combination with the low vulnerability to interference due to the systems optical nature gives a relatively high signal-to-noise ratio.

GOTCHA has been used to instrument several train tracks in the Netherlands. The accuracy of GOTCHA seems to be significantly higher than the accuracy for the WILD system. A test run using 600 passes of a single electrical locomotive had a standard deviation of 1.16 % on the locomotive weight.

GOTCHA has been equipped with an automatic calibration system. This system uses locomotives for calibration, as well as pattern recognition to detect empty passenger cars for calibration. GOTCHA has also been used to detect wheel defects. Further information about GOTCHA can be found at http://www.tagmaster.com/.

Chapter 3

Overview of the instrumented bridges and the toolbox

The work done in this licentiate thesis has resulted in a set of algorithms for performing B-WIM calculations on railway bridges. These methods are described in Appendix B. To make these methods more accessible, they have been built into a MATLAB toolbox, called Twim. This toolbox is described in Appendix C.

3.1 Instrumented bridges

The work in this thesis is based on measurements made on two bridges, the Årstaberg bridge and the Skidträsk bridge. Because the former was instrumented during construction, it was possible to embed strain sensors inside the bridge. The latter bridge was instrumented after its construction. In order to achieve the highest sensitivity, the bridge was also instrumented with strain gauges that measure transverse strain. The transverse strain is much more localized, giving a clearer signal.

The Årstaberg Bridge in Stockholm is a concrete integral bridge with 14.4 m span. Figure 3.1 shows the bridge during its construction. The bridge carries two ballasted railway tracks for traffic heading towards the city of Stockholm. The bridge deck supporting the tracks is 0.8 m to 1.3 m thick and is continuously connected to the 0.9 m thick sidewalls. The bridge was instrumented in 2003 by embedding 4 strain transducers to monitor strains in the longitudinal direction. 3 of the transducers are mounted at mid-span and 1 about 3.3 m from mid-span. More information about this bridge and the installed system can be found in Karoumi et al. (2005).

The Skidträsk Bridge in Norrland (Northern part of Sweden) is a 36 m long simply supported composite bridge, shown in figure 3.2. The bridge carries one ballasted track, and is instrumented with the following sensors:

- 4 strain gauges mounted on the two main steel beams to monitor longitudinal strains.

Figure 3.1 shows the Årstaberg bridge.

- 3 accelerometers on the two main steel beams to monitor vertical deck accelerations.
- 2 B-WIM strain transducers mounted on the soffit of the track slab, monitoring transverse strain. One such sensor is shown in 3.4.
- one air temperature sensor.

Figure 3.3 shows the location of strain gauges and accelerometers at the midspan of the bridge, figure 3.5 shows the cabinet containing all measuring equipment. The cabinet is located inside the bridge, at one of the supports between the two main steel beams. More information on the Skidträsk bridge can be found in Appendix C.

The Skridträsk instrumentation makes it clear that it is possible to instrument existing bridges of types that are not traditionally considered suitable for B-WIM purposes. For a comparison between the transverse and the longitudinal strain, see figure 3.6.

A third bridge, the New Årsta bridge, has been instrumented in another project. This bridge is described in detail in Appendix C. B-WIM trials on this bridge look promising, but no detailed analysis has been performed, and thus no results have been presented.

3.2 Toolbox overview

This section gives a brief overview of the Twim toolbox. For a full description, see the articles included in this thesis. The algorithms used by the Twim toolbox are described in detail in Appendix B. The Twim toolbox and how to use it is described in Appendix C.

Figure 3.2 shows the Skidträsk bridge.

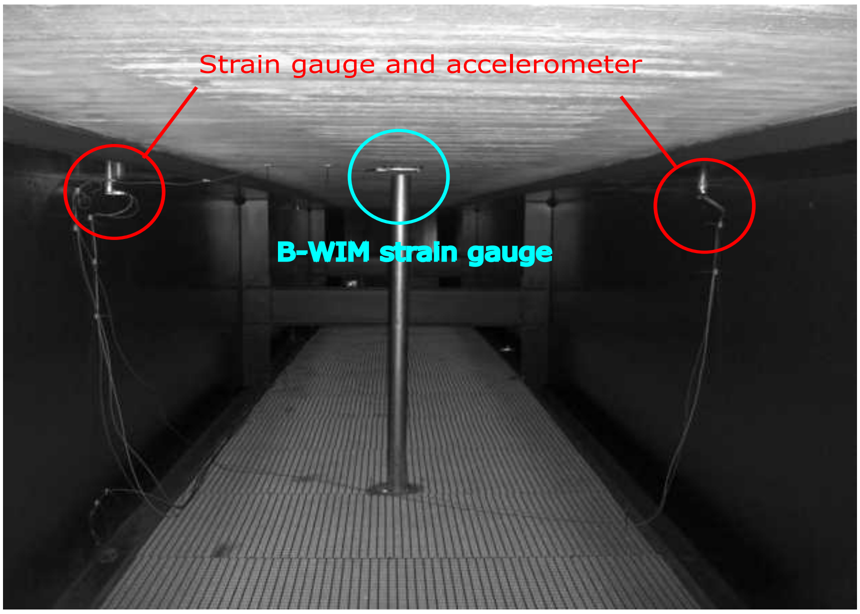

Figure 3.3 shows the placement of the gauges at the mid span of the bridge.

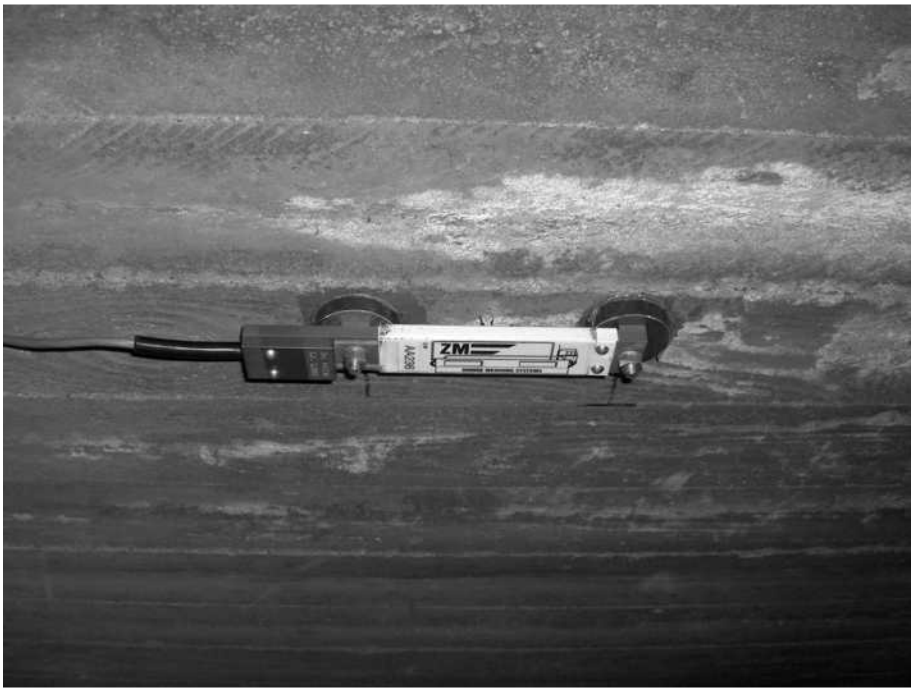

Figure 3.4 shows the placement of the transverse strain gauge mounted on the soffit of the track slab.

Figure 3.5 shows the cabinet containing two data acquisition systems, the computer for storage of recordings and the communication unit.

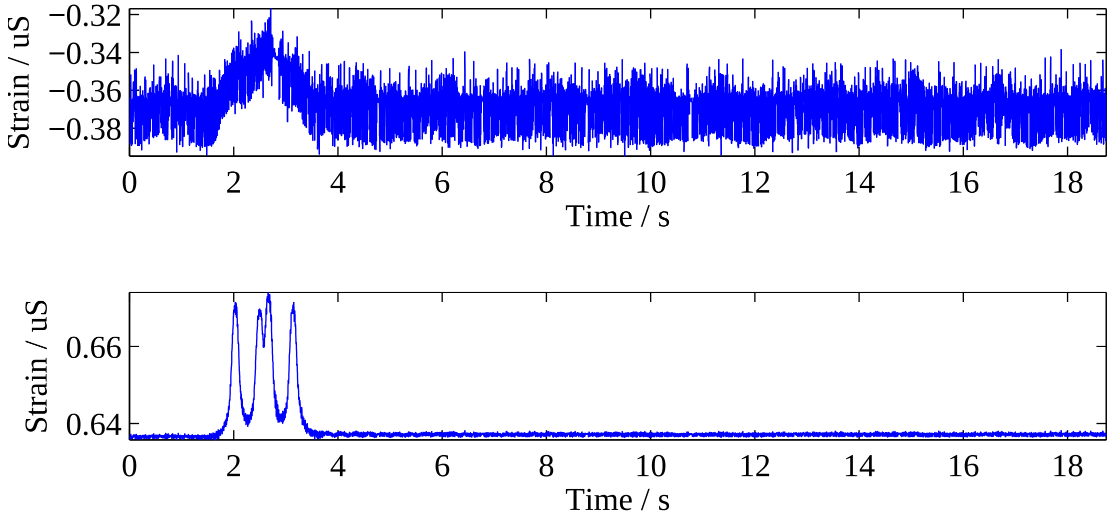

Figure 3.6 shows the difference in signal/noise ratio between longitudinal strain at the bottom of the steel beam (above) and transverse strain on the soffit of the track slab(below). The recording is of a shorter train consisting of two wagons.

The main concept behind the WIM algorithm described in this thesis is that given a train consisting of a set of bogies with a specific bogie load, speed, acceleration and bogie distances, as well as the influence line of the bridge at several sensor positions, an accurate simulated strain curve can be calculated for the train passage. By repeatedly comparing the simulated strain curve with the measured one, and adjusting the train data, one will eventually produce an accurate simulated strain curve.

Twim is designed to provide users who are familiar with MATLAB with a powerful set of WIM-tools that allow them to perform B-WIM calculations without special training. To that end, the toolbox has a small number of functions that perform well defined tasks. These functions are:

- `wim_calibrate`, a function that produces B-WIM calibration data for a bridge. The input for this function is a train signal including information about the weight and axle distance of one or more wagons, sampling rate and some information about the bridge, the output is a set of calibration values.

- `wim_calculate`, a function for performing B-WIM calculations on a recorded signal of a train passage. The input for this function is a train signal and a set of calibration values as returned from `wim_calibrate`, the output is a B-WIM result, including a set of axle weights, axle distances and the speed and acceleration of the train.

- `wim_plot_result`, a function for visualizing the B-WIM detection. The input for this function is a B-WIM result, as returned by `wim_calculate`, the output is a graph showing the real and the simulated strain curve and the positions of each axle. Figure 3.7 is an example of the output of the `wim_plot_result` function.

- `wim_identify`, a function for performing locomotive identification. The input for this function is a B-WIM result, as returned by `wim_calculate`, and a structure containing information about what locomotives to consider, the output is the match value for each locomotive type.

- `wim_do_loop`, an example function for performing real-time continuous B-WIM. This function contains a simple loop that continuously scans a user specified directory for new train signals and performs B-WIM detection on them. It is meant to be user edited.

Together, these functions allow a user to perform B-WIM detection on a bridge with very little work.

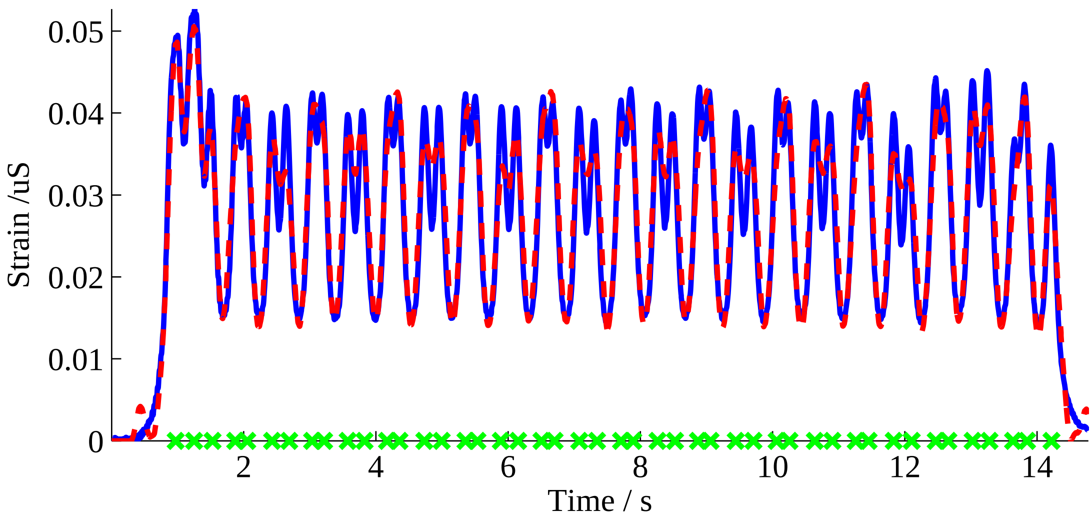

Figure 3.7 shows an example of the output of the wim_plot_result function. The blue line is the strain curve of a regional passenger train passing over the Skidträsk bridge, the dashed red line is the simulated strain curve resulting from the B-WIM calculation. Each green cross represents a detected bogie.

Chapter 4

Additional results

In order to study changes in bridge behavior over time, train passages where recorded on the Skidträsk bridge over the course of 7 months. Roughly half of the recorded train passages where recorded from June 25 to August 30 2006, the rest was recorded from October 20 to November 20 2006. Results from the earliest of these recordings are presented in Appendix C. This chapter contains some additional results including a long term analysis.

4.1 Identified train passages

A total of 1 220 separate train passages were recorded during this period. The B-WIM algorithm, described in Appendix B–C, was applied to these recordings, obtaining 909 identified passages. The rest, 311 files, were removed for the following reasons:

- The most common reason for removal was incomplete recordings; not all recordings held an entire passage. This happened mainly in the early months, due to issues with the recording software, called BRAVE. The BRAVE system is described in Appendix C. This issue has been mostly resolved since then. Figure 4.1 show such an incomplete recording.
- The B-WIM algorithm will fail for trains that drive at irregular speeds when crossing the bridge. The algorithm can deal with minor linear train acceleration, but more complex changes in movement speed will cause the algorithm to fail. Figure 4.2 shows a failed train passage where the train actually stopped on the bridge.
- There are cases where there are significant amounts of disturbance in the recording. Because these disturbances are accompanied by high acceleration values, it is believed that this is caused by wheel defects. Figure 4.3 shows a recording with significant disturbances.

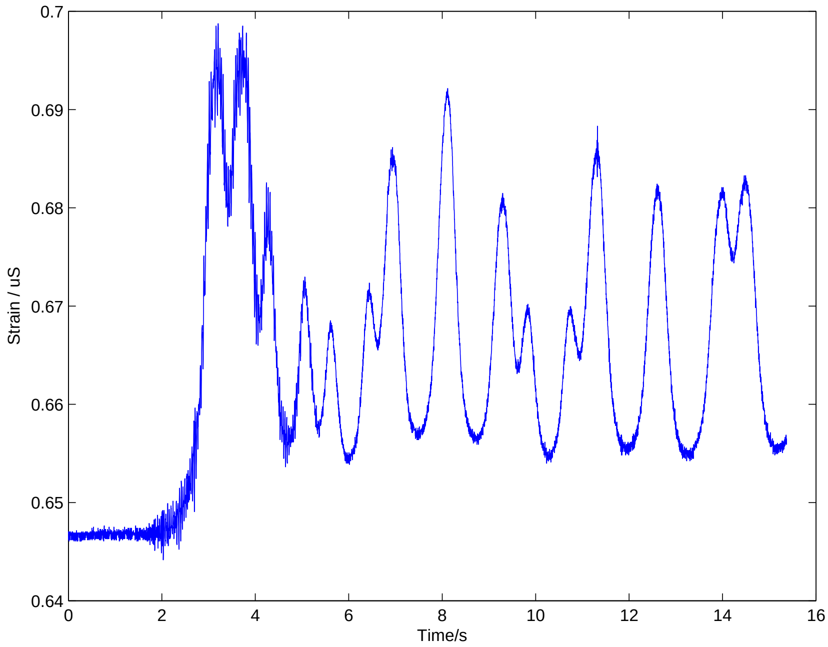

Figure 4.1 show an incomplete recording of a train passage.

- The B-WIM algorithm may fail to detect unloaded wagons on trains with very heavily loaded wagons. This happens when the weight of an unloaded wagon is comparable in size to the error peaks of the strain curve of a loaded wagon. On the bridges tested in this thesis, these error peaks can reach as much as 10 % of the maximum strain. Figure 4.3 shows a recording with large differences in bogie weights.

In order to make the developed B-WIM system more robust, these problems have to be considered when considering future improvements to the system. Filtering trains with high acceleration levels is one possible solution. However, in the case of long trains this becomes a problem. The Steel Arrow, a train consisting of roughly 30 wagons and carrying up to 3 200 metric tonnes of steel from Luleå to Borlänge, passes over the Skidträsk bridge. It is common for at least one of the roughly 240 wheels of a Steel Arrow to contain a large enough defect to give significantly higher than normal acceleration.

4.2 Calibration

Two trains were used for calibration of the system and then discarded. The type of locomotive in these recordings where deduced by looking at train length and the weight distribution between bogies. The first one was a Steel Arrow type train and the second one was a passenger train. These trains were chosen because their strain curves are easy to identify.

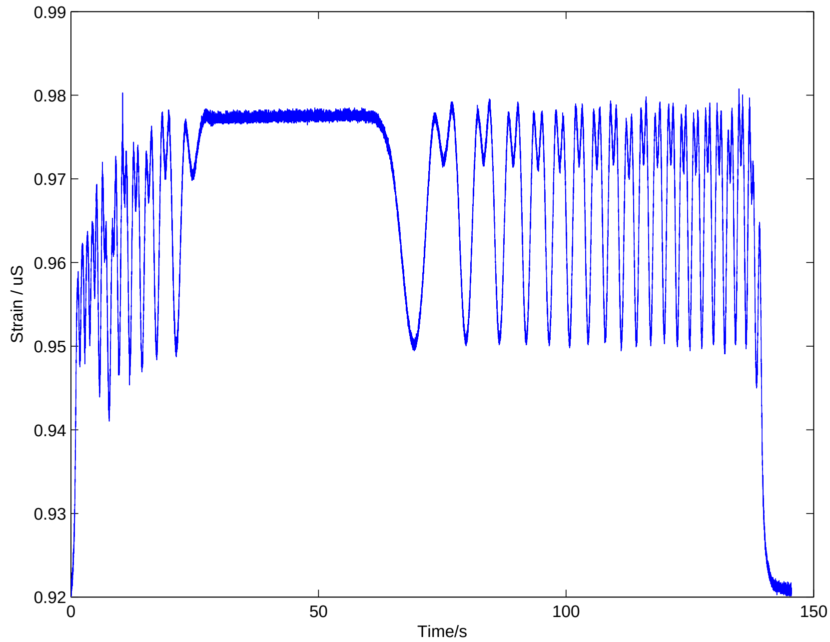

Figure 4.2 shows the passage of a train where the train stopped on the bridge.

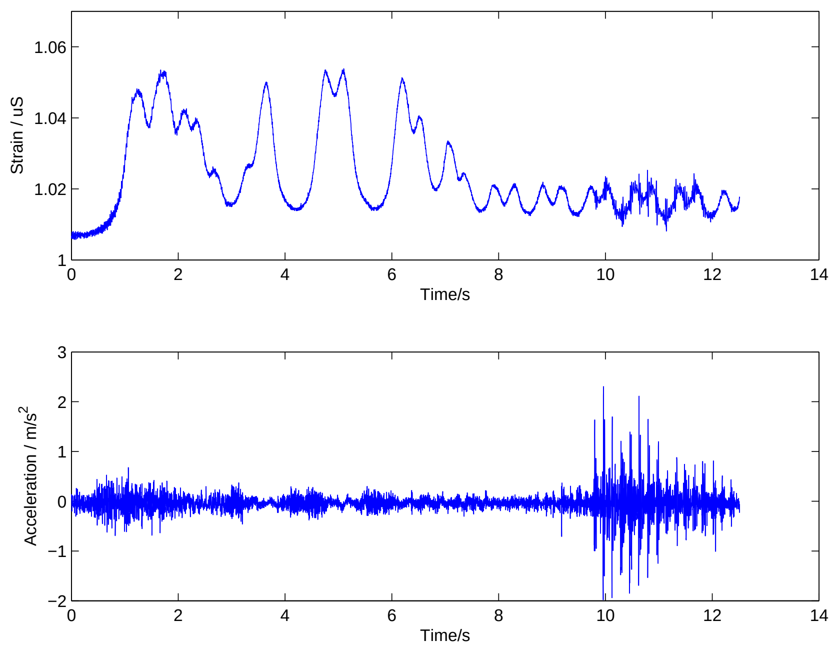

Figure 4.3 shows a recording with large differences in bogie weights and significant disturbances at the end of the recording. These disturbances are most probably caused by a wheel defect, as can be seen from the acceleration curve.

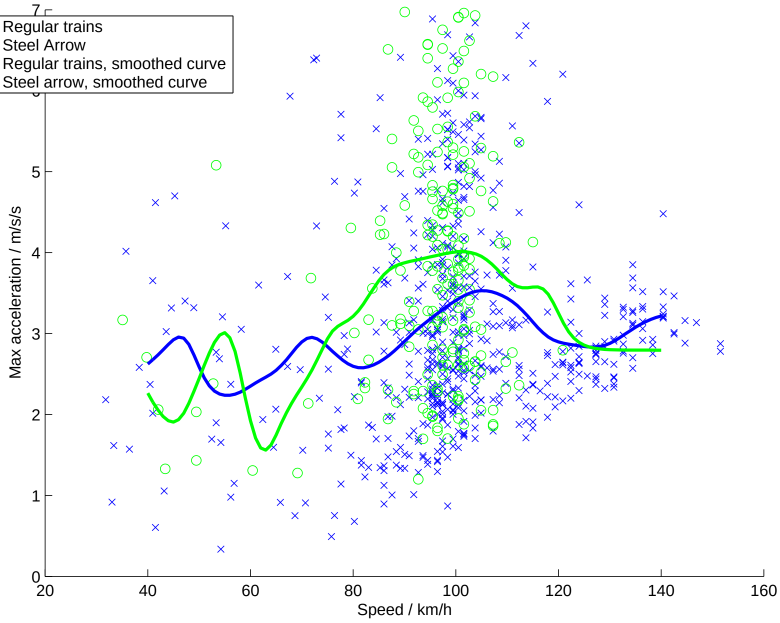

Figure 4.4 shows how the maximum acceleration varies with the speed of a passing train.

The same calibration values were used for all WIM detections during the entire seven month period. This was done in order to check if the influence line of the bridge changed significantly during the testing period. Such changes would imply that basic properties of the bridge or the sensors had changed during the period of measurement.

4.3 Overall trends

Figure 4.4 and 4.5 show how the measured bridge deck acceleration varies with the speed of passing trains. The RMS acceleration shows a mostly linear relation until roughly 100 km/h, where the acceleration meets a plateau, whereas there is a noticeable peak in acceleration at 100 km/h for the maximum acceleration. These results should be compared to figure 4.6, which shows the theoretical acceleration response calculated using a 2D simple but calibrated bridge model. The program DynSolve (developed by Raid Karoumi at KTH) was used for this simulation where the Steel Arrow train is modelled as moving concentrated forces. It should be noted that while the shape of the curves in figures 4.4 and 4.6 are roughly similar, the amplitudes of the curves are not. By examining the actual acceleration curves, e.g. figure 4.3, it can be seen that the acceleration curves contain sharp peaks caused by wheel defects. The theoretical calculations do not take such defects into consideration, thus giving a lower maximum amplitude. Figures 4.4 and 4.5 also show that the vast majority of all Steel Arrow trains travel at approx. 100 km/h.

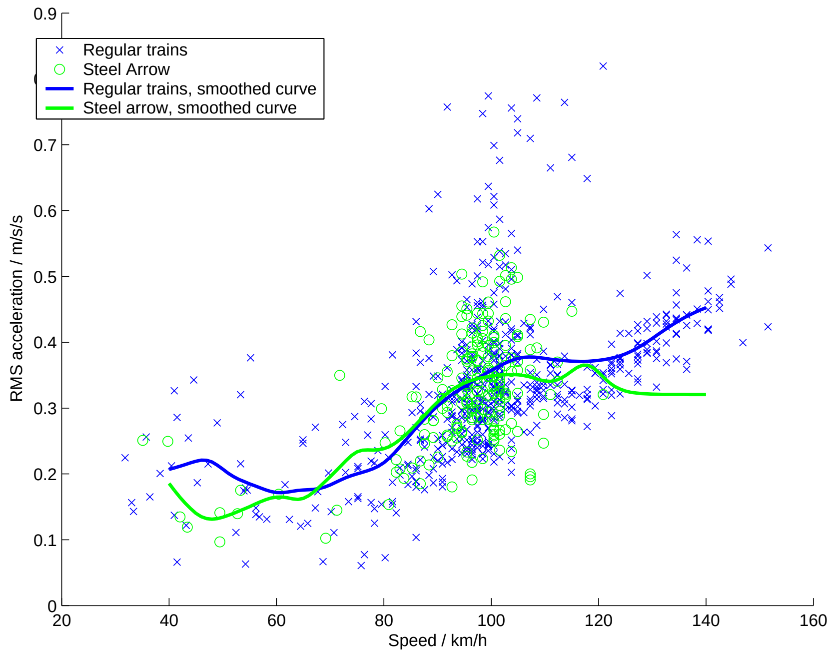

Figure 4.5 shows how the root mean squared acceleration varies with the speed of a passing train.

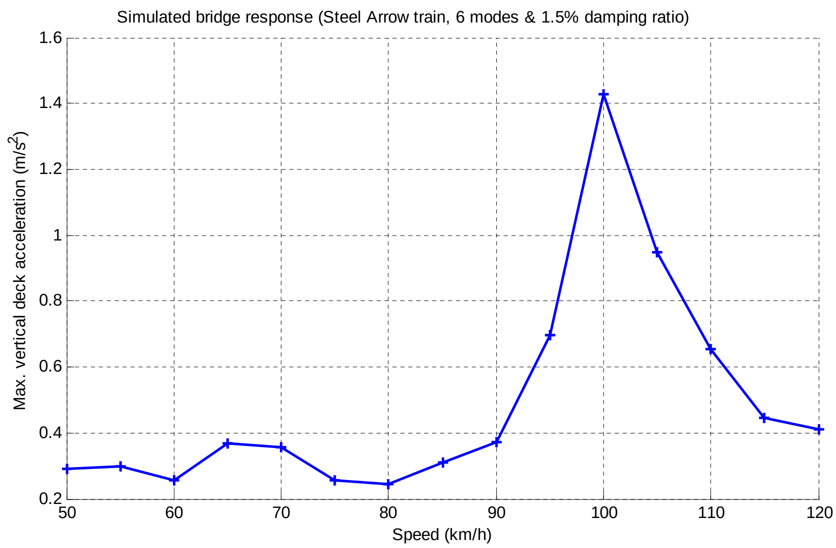

Figure 4.6 shows the results from a FEM simulation of how acceleration varies with the speed of a passing Steel Arrow train. These results where obtained through the DynSolve program by Raid Karoumi.

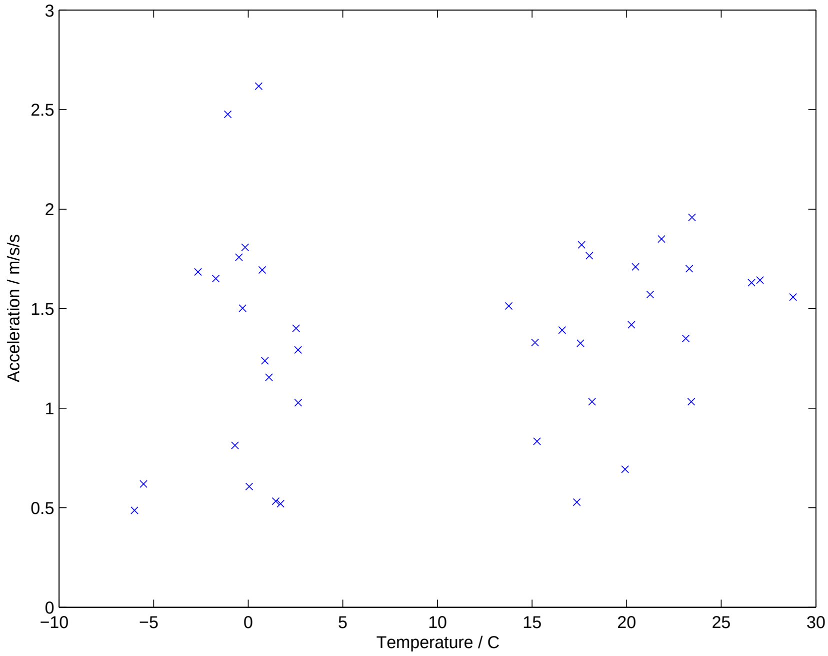

Figure 4.7 shows how the maximum vertical bridge deck acceleration varies with air temperature for a set of identical trains with no noticeable wheel defects passing at approximately the same speed. Figure 3.6 shows the strain curves of one of these passages.

4.4 Temperature's influence on bridge properties

Figure 4.7 shows how vertical bridge deck acceleration varies with temperature. As can be seen, there is no strong temperature dependency in the tested interval. It should be noted that while a few of the measured train passages were done at freezing temperatures, the temperature was never below the freezing point for more than a few days during the measuring period. It can therefore be assumed that the ballast of the bridge is never completely frozen during this period.

4.5 Accuracy of B-WIM results

The accuracy of the B-WIM algorithm could be tested by identifying a set of trains of a known type, and comparing the estimated locomotive weight with the actual weight of the locomotive. A set of trains with only two wagons, passing over the bridge at the same time each day, was chosen to perform this type of estimate. It was found on these trains that the standard deviation of the relative error was 13 %, which should be compared to the 2 % standard deviation that was obtained on the Årstaberg bridge. The results for the Årstaberg bridge are available in Appendix B. It is clear from these results that while the method of measuring transverse strain for B-WIM purposes works, the accuracy of B-WIM when installed on a short integral

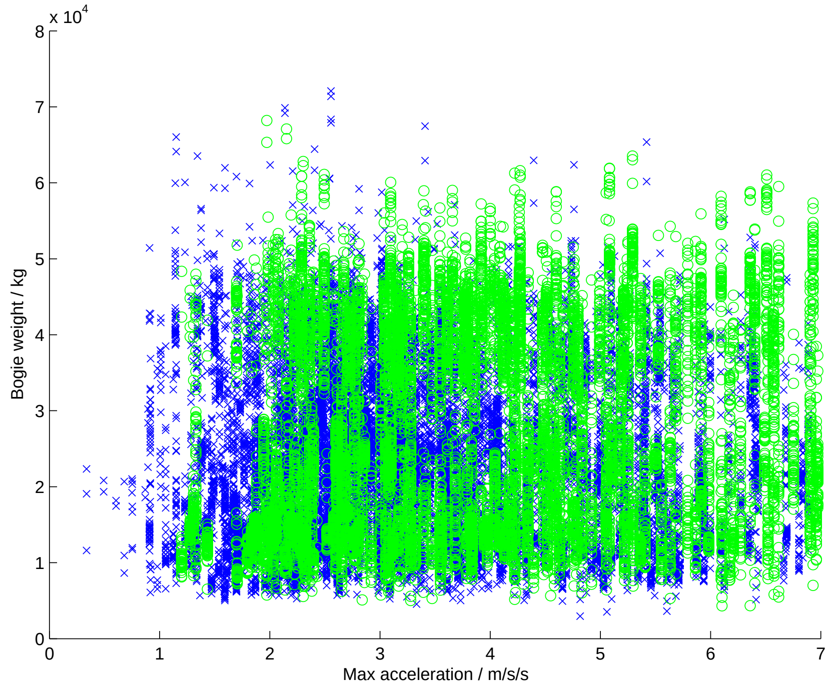

Figure 4.8 shows how the maximum acceleration varies with the bogie weight. Blue crosses are regular trains, green circles are very long trains, most probably Steel Arrow trains.

type bridge like the Årstaberg bridge is significantly higher. This is believed to be mainly because of the considerably larger dynamic effects obtained for the Skidträsk bridge. In order to get results with a satisfactory accuracy for bridges such as the Skidträsk bridge, it is believed that a sensor that measures the global effect of the train on a bridge is needed. Attempts were made to use the strain sensors on the bridge beam for this purpose, but the signal/noise ratio of the signal from these sensors was found to be too low.

In spite of these problems, some notable results can be obtained by looking at statistics of many train passages, as done in figure 4.8. It should be noted that there are several bogies with a calculated weight of 70 tonnes in the figure. Such detections are a result of the reduced precision of the algorithm on the Skidträsk bridge, see section 4.1. It can be seen that even lightly loaded trains (most probably empty Steel Arrow type trains) give rise to significant acceleration.

Chapter 5

Conclusions and future research

5.1 Discussion of the outlined results

This thesis has given an overview of WIM methods developed for use with road traffic. The development of a set of WIM algorithms for railway traffic which is a development of various B-WIM algorithms for road traffic has been described. The toolbox implementing these algorithms and how to use it has also been described. This toolbox has been evaluated through the instrumentation of two bridges and through the collection and analysis of data from these two bridges. The accuracy of the algorithms under ideal conditions on a bridge very suitable for B-WIM has been evaluated in Appendix B. Appendix C and the additional results presented in the previous chapter have focused on performance on less ideal bridges as well as longer term observations and the use of B-WIM to analyze bridge properties like vertical bridge deck acceleration. This latter analysis has given much focus to bridge dynamic behavior like vertical bridge deck acceleration, since this property has been shown to have a large impact on bridge and track deterioration.

5.1.1 Dynamic bridge behavior

While there is no strong weight dependency for the vertical bridge deck acceleration of a train passage, there is speed dependency. There is a noticeable peak in maximum acceleration at 100 km/h. This peak corresponds with theoretical results derived from FEM simulations.

The maximum vertical bridge deck acceleration levels recorded during train passages often exceed the recommended levels of roughly 0.5 g. However, these levels are transient, and the normal acceleration levels are significantly lower. Test results using shake tables performed by Norris et al. (2003) show that such short lived acceleration peaks are significantly less damaging to the ballast, and therefore acceleration levels of up to 1.0 g can be acceptable.

5.1.2 Long term trends

There has been no significant change in vertical bridge deck acceleration during the seven month period under which train passages where recorded.

One of the original goals of the Skidträsk study was to investigate how bridge properties, like damping and influence line change, when the ballast freezes. Unfortunately, the record setting warm winter has made such tests impossible in the current time frame. Such tests will have to be performed in a future project.

5.1.3 Accuracy of the B-WIM algorithm

The accuracy of the WIM algorithm is significantly lower on the Skidträsk bridge compared to the Årstaberg bridge.

Because longer trains like Steel Arrow trains have such a large number of wheels, it is very common to have at least one minor wheel defect in each recorded passage. Because of this, it was not possible to filter out trains with wheel defects without removing nearly all longer trains. Such wheel defects significantly reduces the accuracy of the bogie identification. A system that can detect where on the recording an acceleration peak occurs and thereby ignores that specific segment would be needed to provide higher accuracy in bogie load estimates.

Even on shorter trains, the standard deviation of the relative error in locomotive weight was 13 %, compared with 2 % on Årstaberg. This is probably caused by increased bridge dynamics that are inherent in longer bridges with comparatively small mass. The lower accuracy of the results on the Skidträsk bridge mean that direct estimates of the weight of individual bogies are not useful, but interesting overall trends can still be seen. For example, the speed vs. acceleration curves from the Skidträsk bridge imply that bridge dynamics would not increase if the marching speed of the Steel Arrow trains where increased above the current 100 km/h.

5.2 Suggested future work

There are several venues for future research with the methods described in this thesis. The following section gives a few suggestions for future research topics.

5.2.1 Further developments of the described methods

- Attempt to differentiate between single axles and bogies, in order to increase the accuracy of single axle suspensions.
- Attempt to use the described algorithms on train passages at higher speeds. To date, no high speed train passages have been recorded using the B-WIM

system described in this thesis. It is possible that dynamic effects such as dynamic amplification become more prominent at these speeds.

- Attempt to use the described algorithms on types of bridges that are not included in this study.
- Attempt to combine sensors measuring very local effects for accurate axle detection with sensors measuring global load effects for weight estimates with minimal dynamic effects. This was attempted on the Skidträsk bridge with no increase in accuracy. It is likely that the very low signal to noise ratio of the non-B-WIM sensors, demonstrated in figure 3.6, prevented any potential gain in accuracy from having a sensor that measures global load effect.

By further developing the available methods, it is hoped that even more accurate WIM results can be achieved, and that more types of bridges can be used for B-WIM purposes.

5.2.2 Studying bridge behavior

- Study the long term changes in bridge behavior. Cracks, fatigue and other aging effects cause changes in the bridge properties such as the influence line.
- Study seasonal changes in bridge behavior. Very little is known about the effects of freezing and other weather effects on bridge properties like the dynamic response.
- Study the effect of maintenance work and repairs on the bridge behavior.

If better information on the condition of bridges can be obtained through B-WIM, this information can be used to greatly reduce the maintenance costs for bridges. These cost reductions can be realized in the form of delaying unneeded maintenance work. When building new bridges, costs can also be reduced by building bridges that are better suited to the actual traffic flow and the actual weight distribution of the traffic at the bridge site.

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Appendices

Appendix A

Monitoring traffic loads and dynamic effects
using an instrumented railway bridge

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Monitoring traffic loads and dynamic effects using an instrumented railway bridge

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Abstract

This paper presents a cost-effective method for the assessment of actual traffic loads on an instrumented bridge. The instrumentation of a newly constructed integral-type railway bridge in Stockholm (Sweden) is described. A complete “Bridge Weigh-in-Motion” (B-WIM) system, with axle detection and accurate axle-load evaluation, was implemented using only four concrete embedded strain transducers. A temporary accelerometer was attached to the edge beam of the bridge to evaluate the eigenfrequencies, predict possible wheel/rail defects, and check whether the acceleration limit value for ballast instability (as given in railway bridge design codes) is exceeded. The main objective of the monitoring project has been to increase the knowledge of actual traffic loads and their effect on railway bridges, through both measurements and numerical simulations. Some very early but representative results are presented, and the efficiency of the algorithms and usefulness of the monitoring program highlighted.

Keywords: Bridge; Railway; Traffic loads; Weigh-in-motion; Monitoring; Dynamics

1. Introduction

Until recently, most of the research in the area of bridge design has concentrated on the study of the strength of materials, and relatively few studies have been performed on traffic loads and their effects. It is, however, widely known that dynamic effects due to moving trains on bridges can be very large, leading to bridge deterioration and, eventually, increased maintenance costs and reduced service life of bridge structures. In spite of this, permissible axle loads and speeds are increased in order to efficiently make use of the initial costs of investment in infrastructure. In the process of assessing old bridges, or of designing new bridges, there are generally two approaches for checking their true capacity, namely: (i) use of “design trains” specified in design codes for railway bridges, and inclusion of the additional dynamic loads from moving trains by multiplying the static effect by a so-called dynamic amplification factor (DAF) that is determined from simple formulas; (ii) perform a more accurate analysis using simulations of “real” moving trains and calculation of the actual dynamic response.

One can, of course, question the correctness of the traffic loads, current safety factors and DAFs utilized [1]. In fact, the “design trains” and DAF formulas in design codes for railway bridges are often seen as very conservative in nature and are believed to be unsuitable to current traffic conditions. Thus, within the bridge engineering community, there is today a considerable interest in the problem of measuring actual traffic loads and their dynamic effect on bridges. Therefore, research at the Royal Institute of Technology (KTH) has concentrated on traffic loads in general and their actual effect, in line with the latter of the above two approaches. Such a dynamic analysis is however complicated, and one has to take into consideration that the bridge response is influenced by the interaction

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between the train and the bridge structure [2]. As expected, dynamic analyses have shown that bridge damping and the condition of the rail surface have the largest influence on the dynamic response. For smooth surfaces, bridge–vehicle interaction could be neglected, and train wheel loads can be modeled as constant moving forces. For long trains with repeated axle spacings, resonance occurs, giving very high dynamic amplification factors and deck accelerations, when the bridge frequency is close to this excitation frequency. This might result in ballast instability and derailment [7].

Consequently, several bridges in Sweden have recently been instrumented by the authors. Strain transducers have been placed on the soffit or embedded in the bridge deck to collect data that makes it possible to calculate actual axle loads to be used for analysis. In addition, accelerometers have been attached to the edge beams to provide the monitoring projects with valuable additional results. As a result, this relatively inexpensive instrumentation makes it possible to: (i) determine vehicle characteristics such as speed, axle distances, and static axle loads, all of which are usually collectively referred to as a “Bridge Weigh-in-Motion” (B-WIM) system; (ii) measure the true dynamic response, thereby determining the DAFs from simulations.

To demonstrate the usefulness of monitoring railway bridges, this paper focuses on and describes the instrumentation and monitoring of a newly constructed integral-type railway bridge in Stockholm (Sweden). The fundamental aim of this study is to increase the knowledge of actual traffic loads and their effects on railway bridges, through both measurements and numerical simulations. The B-WIM results presented indicate that the algorithm developed has the potential to provide accurate WIM data such as static axle loads, axle distances and speeds. The authors anticipate that this monitoring program will result in a more appropriate design methodology for new bridges. For existing bridges, the knowledge gained will help to determine whether there exists sufficient reserve in strength to accommodate the desired increase in axle loads and speeds.

2. Objectives of the monitoring program

As mentioned earlier, the instrumentation described in this paper is one of several recent railway bridge instrumentations in Sweden that are and will be performed as part of a project financed by the Swedish National Railway Administration (Banverket). The fundamental aim/objective of the instrumentations is to study actual traffic loads and their effect on railway bridges and thereby increase knowledge through measurements and numerical simulations.

Furthermore, all rail traffic passing over this specific bridge also passes over the New Årsta Railway Bridge, a bridge under construction that was also instrumented by the authors [3]. This bridge is however very different from the bridge described here, as it is a very complex, slender and therefore optimized multi-span concrete structure carrying two unballasted tracks. Consequently, this gives an opportunity to investigate how different bridges, having ballasted and unballasted tracks, respond to the same trains.

Moreover, the objectives of the instrumentation of this and other railway bridges within this project are: (i) to measure actual traffic loads and study the feasibility of the instrumentation for B-WIM; (ii) to compare measured with numerically simulated dynamic responses to improve the knowledge of dynamic effects of crossing trains and actual DAFs; (iii) to collect vertical acceleration data to investigate acceleration levels (especially concerning the limit value for ballast instability on new bridges given in design codes), eigenfrequencies, damping, and possible wheel/rail defects; (iv) to develop a better theoretical understanding of the effect of ballast on bridge dynamics.

3. Bridge description

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

The bridge has a span of 14.4 m, is made of reinforced self-compacting concrete and is of the integral type (Fig. 1), i.e. the construction is continuous as it is constructed without movement joints at the junctions between the deck and the abutments. The deck supporting the tracks is 0.8–1.3 m thick and the sidewalls are 0.9 m thick. The sidewalls are also continuously connected to a 1.0 m thick bottom slab.

4. Instrumentation and the data acquisition system

Four special resistance strain transducers (Fig. 2), produced at The Royal Institute of Technology (KTH), were embedded in the concrete section of the deck supporting the two railway tracks. The total length of each transducer is 300 mm, and between the two anchor plates, 50 mm in diameter, each transducer contains a strain element made of a steel tube, 10 mm in diameter, to which four strain gauges are attached. The strain gauges are all connected as a full Wheatstone bridge. The cables are routed inside the steel tube, which has indeed been encapsulated with several coatings for protection and to ensure that the deformations are only introduced at the anchor plates. The data acquisition system MGCplus from Hottinger Baldwin Messtechnik (HBM) was chosen, connecting each strain transducer to an ML55B amplifier.

As the main interest is in measuring/calculating actual traffic loads and load effects on the high speed line, three of the transducers were placed under that track (Fig. 3). Only one transducer, called U3, was placed under the second track, a track only for commuter trains and therefore chosen to be of less interest in this project. All transducers were oriented to measure the longitudinal strains and were placed

Fig. 1. The instrumented integral bridge at Årstaberg.

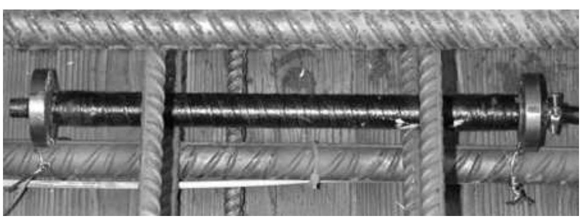

Fig. 2. A resistance strain transducer, produced at The Royal Institute of Technology (KTH) in Stockholm.

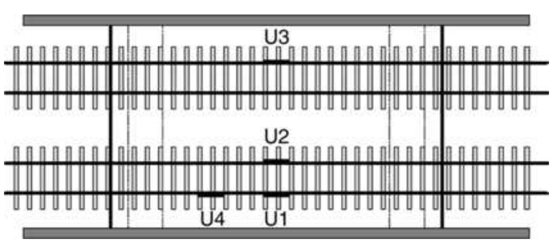

Fig. 3. Illustration of the location of sensors U1–U4, embedded in the bridge deck.

approximately 100 mm from the bottom of the concrete section.

In addition to the above described instrumentation, an accelerometer for measuring vertical accelerations was installed temporarily. It was mounted onto the edge beam close to the mid-span to measure the bridge deck vertical acceleration. The scanning frequency for all sensors was set to 1000 Hz.

5. The FE model

For the verification of the measurements and as a basis for analysis and numerical simulations to be performed for the dynamic studies listed in Section 2, a simple 2D FE model of the bridge has been developed and implemented in the MATLAB language. A bridge damping ratio of 0.019 was used, according to Eurocode [7]. For simplicity, the beneficial effect of the soil behind the abutment walls was neglected. The model and the moving train simulations are made using programs developed by Karoumi [2].

The simulated response takes the train/bridge interaction into account and is based on the mode superposition technique including the first 25 modes of vibration.

In addition, a more detailed 3D FE model is being developed in ABAQUS to give a more realistic model to be used in future verifications and simulations.

6. The B-WIM algorithm

B-WIM (or Bridge Weigh-in-Motion) is the process of converting an instrumented bridge to a scale for weighing crossing vehicles. This section describes the implemented railway B-WIM algorithm which is partly based on previously published research done by Quilligan [4,5]. The B-WIM algorithm, which has been implemented in the MATLAB language, produces the following results: number of axles; position of each axle (axle distances); static load of each axle; speed and acceleration of the train; direction of the train; track on which the train is crossing.

The resolution of the B-WIM algorithm depends on the bridge type and whether the track is ballasted or not. Consequently, for most ballasted railway bridges the individual axles of a bogie cannot be separated and therefore the B-WIM algorithm incorrectly identifies a bogie as one axle. However, this has not been found to decrease the algorithm's efficiency. Details of the algorithm will be found in [6] and it consists of the following main steps:

1. Loading of the calibration data, including the influence line for each sensor.
2. Calculation of the speed of the train.
3. Initial guess of the axle positions and the axle loads.
4. Calculation of a simulated strain curve based on the above obtained information.
5. Adjusting of axle positions, axle loads, speed and acceleration of the train to minimize the difference between the calculated strain curve and the actual strain curve.

The difference minimization is a non-linear optimization problem which can be defined as minimizing

$$O(y) = \sum (L_c(y) - L_m)^2 \quad (1)$$

to find $y = \{v, a, p_1, p_2, \ldots, p_N, m_1, m_2, \ldots, m_N\}$ where $O(y)$ is the objective function; v and a are the speed and acceleration of the train respectively; p_n and m_n are the position and the load of the n-th axle respectively; $L_c(y)$ is a function generating a strain curve given the above-mentioned train properties; and L_m is the actual strain curve.

Concerning the speed calculation two different methods are implemented where the simplest but less accurate relies on identifying a peak on the strain curves of both sensor U1 and sensor U4 and evaluating the time difference between the two peaks. Then, since the exact distance between sensors U1 and U4 is accurately known, the speed can easily be calculated. It is of course desirable to know the accuracy of each speed calculation method and for that reference values from a laser speed measuring pistol, commonly used by the Swedish police, has been used.

Obviously, the B-WIM system needs to be calibrated to determine an influence line for each sensor. This is usually done by running locomotives with known axle loads and speeds over the bridge. System calibration can also be performed automatically, i.e. by using well-known locomotives from random crossing traffic without requiring user interference [6]. Furthermore, as the stiffness of the bridge may change in time due to e.g. cracking, settlement or changes in soil stiffness from winter to summer, calibration of the system needs to be redone at regular intervals.

7. Results

7.1. Eigenfrequencies

The simplest 2D FE model of the bridge gives four bending modes under 30 Hz: 6.2, 9.2, 12.7 and 24.8 Hz. The first two of these are illustrated in Fig. 4.

These frequencies or, more correctly, frequencies close to these may be identified in the analysis of the free vibration part of a measured acceleration signal obtained from a crossing train (Fig. 5). However, the first bending mode cannot be identified, which is indeed logical since the accelerometer is placed close to the mid-span. In addition, many other frequency peaks are also obtained which might

Fig. 4. The first two bending modes of vibration calculated from a simple 2D bridge model. The rectangle of dotted lines represents the “box” shape created by the top slab, abutments and bottom slab.

be torsional modes that are excited due to the eccentricity of the crossing train. These vibration modes can later be verified using measurements with two accelerometers, one at each edge beam, and with a 3D FE model. To start with however, the results obtained so far indicate that the simple 2D FE model seems to be an adequate model.

7.2. Strain calculations

Fig. 6(a) and (b) show the measured and simulated strain histories at the location of sensors U1 and U4. In this particular case the crossing train had a speed of 32 km/h and consisted of two Swedish RC3 locomotives at each end and six wagons in between. As can be seen, the simulated curve, using the simple 2D FE model and the mode superposition technique including the first 25 modes of vibration, agrees fairy well with the measured curve. In addition, it is interesting to notice that by looking at the curves the locomotives and the wagons can easily be identified; the first two peaks to the left and the right are the locomotives’ bogies and the peaks between them give the bogies for the six wagons in between.

As expected, the readings from U1 and U4 differ as the longitudinal locations of these sensors relative to mid-span are not the same; see Fig. 3. Although not shown here, sensor U3 gives similar results to sensor U1 but with different amplitude, depending on which track is being loaded.

The comparison between simulated and measured strains shows a convincing agreement. However, the maximum measured strain was approximately 8 μs while the maximum simulated strain was around 11 μs. The authors believe that this disagreement is the result of using a low modulus of elasticity, i.e. the bridge is actually stiffer than assumed. Nevertheless, the strain comparison further increases the confidence in the simple 2D FE model’s suitability. In the next step, an updating of this FE model is needed to achieve a better agreement between measurements and simulations.

7.3. B-WIM results

A set of measurements using the four strain transducers and the laser speed measuring pistol was done for 33 train sets. The speeds of the recorded trains (commuter trains, high speed trains, and regional trains) varied between 38 and 114 km/h. These speeds may seem very low, especially for high speed trains, but this was due to speed restrictions at the specific time of measurements.

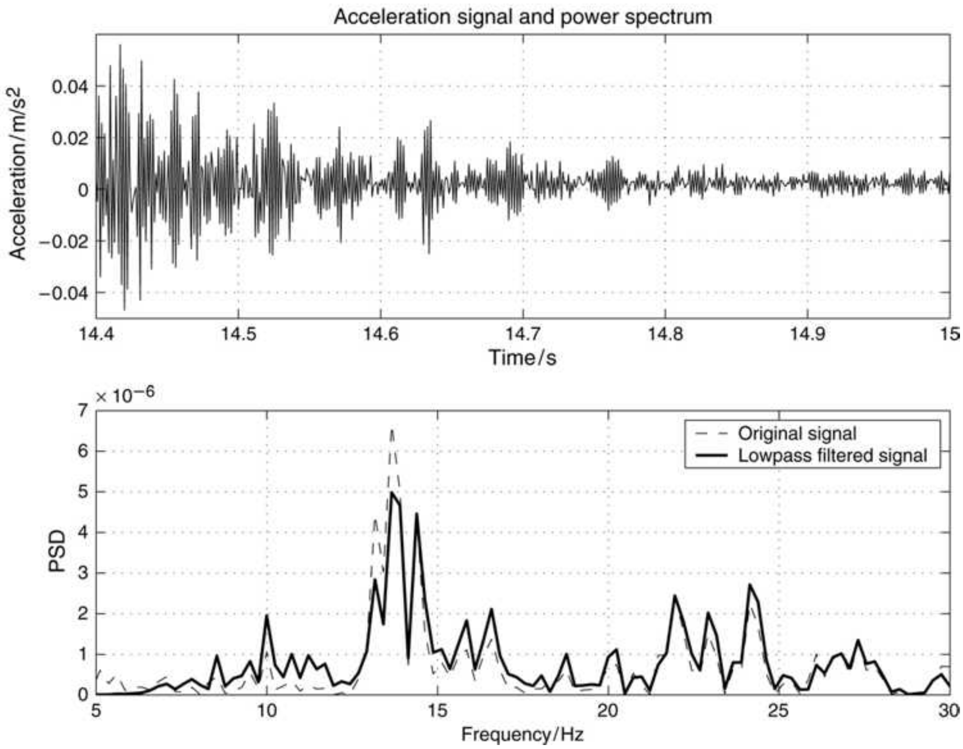

Fig. 5. Free vibration signal shortly after the train has crossed the bridge and the corresponding frequencies (power spectrum).

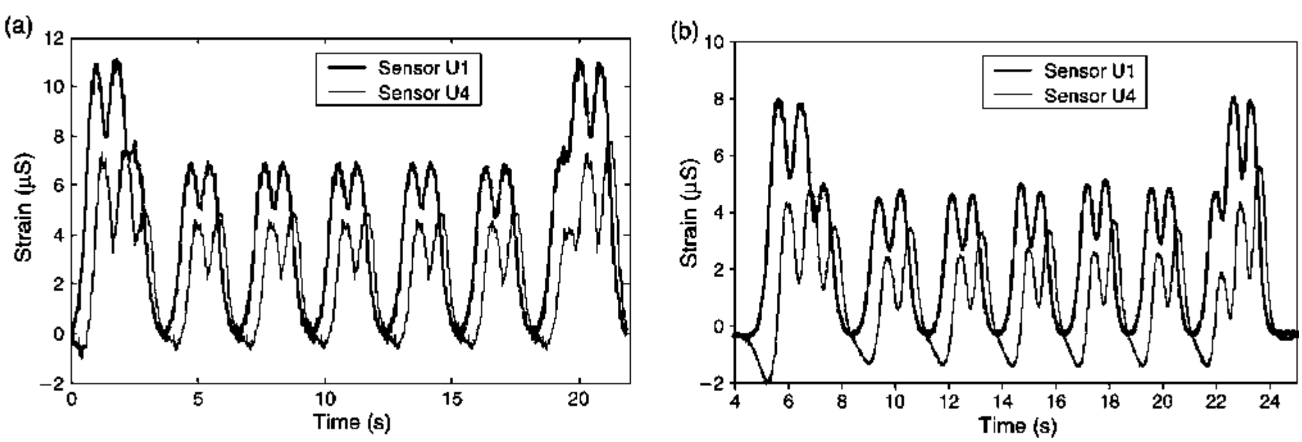

Fig. 6. (a) Simulated dynamic strain histories and (b) measured dynamic strain histories at the locations of sensor U1 and U4. The train crossing the bridge consists of two Swedish RC3 locomotives at each end and six wagons in between.

The standard deviation of the error in speed calculations is about 5%. One should bear in mind that such errors can originate from various sources; the train acceleration (speed measurements were done about 100 m before the bridge); the laser pistol not being completely parallel to the train at the time of measuring; and other sources of errors involving the speed pistol.

For all the 33 registered train sets the locomotives' static axle loads were well known. Thus, these were used to verify the accuracy of the implemented B-WIM algorithm. The implemented locomotive identification algorithm correctly identified all locomotives, which was not a very difficult task since only three types of locomotives were measured, all with significant differences in both axle loads and axle distances.

Fig. 7 shows how a locomotive's calculated gross weight varies with its real gross weight. The standard deviation of the error in estimated gross weight is approximately 2%. Correspondingly, the estimated bogie loads have an error of approximately 2.5%. Fig. 7 also shows how the error in the locomotive's calculated gross weight varies with the speed of the locomotive. As can be seen, there is

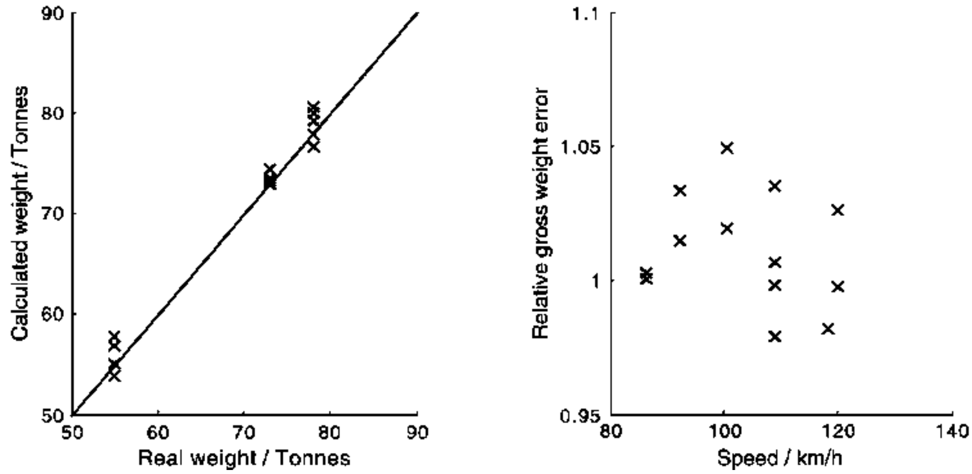

Fig. 7. The variation of calculated gross weight with real gross weight (left) and the variation of the estimated error depending on the calculated speed for 13 trains (right).

no obvious tendency towards speed dependency according to the calculation of axle loads. However, it should be noted that the variations in speed were small and that such tendencies might well be noticeable at higher or lower speeds. It should also be noticed that several of the trains used to produce Fig. 7 had more than one locomotive. With that in mind, there appears to be a slight co-variation in the error of multiple locomotives in the same train.

7.4. Acceleration results

The accelerometer was mainly introduced and used to check the maximum measured vertical deck acceleration levels since design codes for new railway bridges [7] specify an upper limit of 3.5 m/s^2 for frequencies up to 30 Hz (ballast instability criteria). However, no measured signal indicates accelerations over 3.5 m/s^2 and they are of course further decreased when a low-pass filter of 30 Hz is used. However, it is important to mention that these low accelerations are probably due to low train speeds and the new smooth track. Higher accelerations might well be obtained at higher speeds or for trains other than those included in this preliminary measurement campaign.

In addition, the system (acceleration measurements) can be used to give an indication of whether the rail surface is getting rougher and/or a wheel in the crossing train has a defect, a so-called wheel flat. Such information is indeed very useful and can be used to control the maintenance process for the bridge and the wheels of the crossing trains. Fig. 8 actually illustrates this phenomenon as the acceleration signal's distinct peak where the arrow is pointing looks nothing like the acceleration in the rest of the signal. Therefore, a signal like this could indicate a possible wheel defect for the power car of this train.

Due to the content of high frequencies it is interesting to note that the spectrogram in Fig. 8, where white symbolizes high intensity and grey symbolizes low intensity, also clearly indicates the number of locomotives/wagons.

8. Conclusions

This paper has presented details of the instrumentation of an integral-type railway bridge, aimed at studying actual railway traffic loads and their effects on bridges, as well as the ongoing development and testing of the Bridge Weigh-in-Motion (B-WIM) system. Some very early results have been presented, and these show the good quality of the measured data and the usefulness of the implemented B-WIM algorithm. The B-WIM results presented from the few field tests that have been conducted so far indicate that the algorithm developed has the potential to provide accurate WIM data such as static axle loads, axle distances and speeds. Furthermore, it is believed that the system developed will provide valuable information on the quality of the rail surface and of the wheel tread, leading to lower maintenance costs. This will, however, require a great deal of study and testing. On the other hand, if it is proven to work well in practice (giving sufficiently accurate results), it is believed that railway authorities and operators will be very interested in this measuring system as it is very cost-effective and based on components with proven technology.

To summarize, possible benefits of the monitoring system developed/implemented are: (i) it will allow the determination of static axle loads and dynamic amplification factors (DAFs); (ii) it will provide statistics on axle loads, axle distances, speeds, etc. that can be used to identify/monitor trends in railway traffic which, in turn, can be used to develop "design trains" for railway bridge codes; (iii) it will provide data for the quality control of wheel tread and rail surface, leading to lower bridge/track maintenance costs; (iv) it will permit monitoring of long-term bridge performance for the assessment of structural integrity as well as for damage detection studies.

Finally, the authors anticipate that this monitoring program will indeed result in a more appropriate design of new bridges. For existing bridges, the knowledge gained will help to determine whether there exists sufficient reserve in

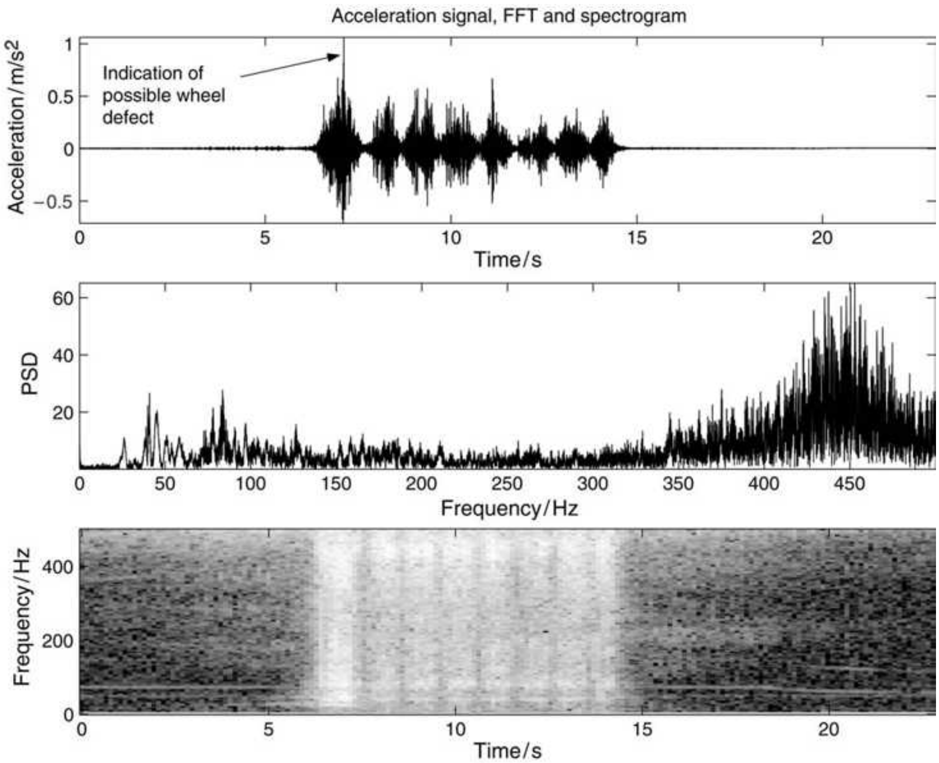

Fig. 8. A complete acceleration signal that indicates a possible wheel defect for the power car and an illustration of the content of high frequencies due to wheel/rail contact. Notice the clear indication of the power car and the number of wagons in the lower plot, where white symbolizes high intensity and grey symbolizes low intensity. Thus, the illustrated signal comes from a train with one power car and seven wagons.

strength to accommodate any desired increases in axle loads and speeds.

Acknowledgements

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Appendix B

Implementing Bridge Weigh-In-Motion for railway traffic

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Implementing bridge weigh-in-motion for railway traffic

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Abstract

This paper focuses on implementing existing bridge weigh-in-motion technology on railways. Using only simple instrumentation with four concrete embedded sensors, a complete WIM system with axle detection, weighing, track detection and attempted identification of locomotives was implemented on a bridge with multiple railway tracks. The results and the effectiveness of this type of sensor setup is discussed.

Keywords: Bridge; Railway; Train; Weigh-in-motion; WIM; Influence line; Calibration; Speed measurement

1. Introduction

Until recently, most of the research in the area of bridge design has concentrated on the study of the strength of materials and relatively few studies have been performed on assessing actual traffic loads and their effects on bridges. As a result, the correctness of the traffic loads, current safety factors and dynamic amplification factors used today by bridge engineers for design and assessment of bridges can be questioned [1].

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

- Determine vehicle characteristics such as speed, axle distances, and static axle loads. This is usually referred to as bridge weigh-in-motion (B-WIM) system, as such an installation converts the bridge into a scale that weighs traffic while moving over the bridge [5,6].
- Measure the true dynamic response. The dynamic amplification factors can then be determined using simulations based on measured speeds, static axle loads and distances.

This paper describes the instrumentation of a newly constructed integral type railway bridge in Stockholm. The fundamental aim of this study is to increase the knowledge of actual traffic loads and their effects on railway bridges through measurements and numerical simulations. For a more detailed description of the instrumentation objectives, etc., see [2].

2. Description of the bridge

Three railway bridges have been built at the new Årstaberg railway station in Stockholm, Sweden, during the year 2003. One of these bridges, carrying two ballasted railway tracks for traffic heading towards the city was instrumented during it's construction (Fig. 1).

The bridge has a span of 14.4 m, is made of reinforced self compacting concrete and is of the integral type, i.e. the construction is continuous as it is constructed without

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Fig. 1. The instrumented integral bridge during construction at Årstaberg.

movement joints at the junction of the deck with abutments. The deck supporting the tracks is 0.8–1.3 m thick and the sidewalls are 0.9 m thick. The sidewalls are also continuously connected to a 1.0 m thick bottom slab.

For the verification of the measurements and as a basis for analysis and numerical simulations, FE-models of the bridge have been developed. Some simulations of the dynamic response of the passing train are made using a program developed by the second author and described in [3]. The results of these simulations are not the focus of this article and are not presented here; however, they can be found in [2], and future reports.

3. Description of the instrumentation and data acquisition system

Four special resistance strain transducers (Fig. 2), produced at The Royal Institute of Technology (KTH) in Stockholm, were embedded in the concrete section of the deck supporting the two railway tracks. The total length of each transducer is 300 mm. Between the two anchor plates, 50 mm in diameter, there is a strain element made of a steel tube, 10 mm in diameter, to which four strain gauges are attached. The strain gauges were connected as a full Wheatstone bridge. The cables are routed inside the steel tube, which was later encapsulated with several coatings for protection and to ensure that the deformations are only introduced to the anchor plates. The data acquisition system MGCplus from Hottinger Baldwin Messtechnik (HBM) was chosen for this instrumentation, connecting each strain transducer to a ML55B amplifier.

As the main interest is to measure/calculate actual traffic loads and load effects on the high speed line, three of the

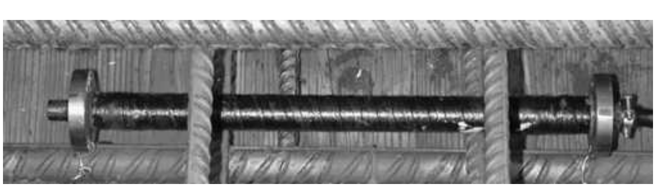

Fig. 2. Resistance strain transducer produced at The Royal Institute of Technology (KTH) in Stockholm.

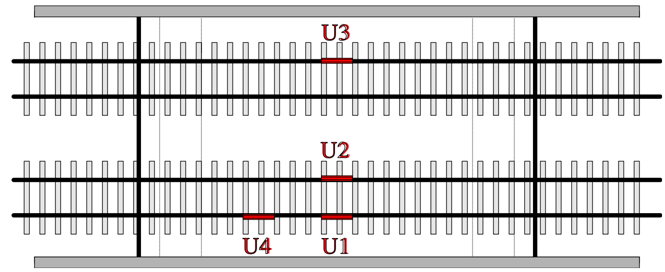

Fig. 3. Location of sensor U1–U4, embedded in the bridge deck.

transducers were placed under the high speed track, while only one transducer, U3, was placed under the second track which is for commuter trains (Fig. 3). Since multiple sensors are located at the centre of the bridge, but beneath the different tracks, it can be easily determined in which of the two lanes a train is running. In the case of multiple trains passing the bridge simultaneously, a low resolution splitting of the signal into one signal for each track should also be possible, but since this has yet to occur, the precision of such a splitting cannot be verified.

4. B-WIM algorithm

B-WIM or bridge weigh-in-motion is the process of converting an instrumented bridge into a scale for weighing passing vehicles. B-WIM for railway traffic is a subject which has been much less thoroughly studied than B-WIM for road traffic. As it turns out, there are several differences between the two:

- Even under heavy traffic, two trains never simultaneously cross a moderately long bridge on the same track. In fact, we have been unable to record a single instance of more than one train on the same bridge on different tracks.
- The dynamic behavior of the train seems to have a limited effect on the B-WIM signal.
- Because of the length of a train set, the speed difference between the first and last wagon of the train can be significant on bridges such as the Årstaberg bridge, which is located near a station.

None of these differences fundamentally change the premise of problem. The first two differences only serve to make the problem somewhat easier, while the third one adds an additional variable that needs to be calculated and taken into account, namely the acceleration.

This section describes the implemented railway B-WIM algorithm which is partly based on previous research by Quilligan [6]. The B-WIM algorithm, which has been implemented in the MATLAB language, produces the following results:

- Axle distances.
- Static axle loads.
- The speed and acceleration of the train.

- The direction of the train.
- The track on which the train is crossing.

Of course, as the resolution of the B-WIM algorithm depends on the bridge type and if the track is ballasted or not, for most bridges, the individual axles of a bogie cannot be separated. Consequently, for such bridges the B-WIM algorithm incorrectly identifies bogies as axles. This has not been found to decrease the algorithm's efficiency. The algorithm works using the above listed values to calculate a simulated strain curve. The square difference between this curve and the actual measured load curve is then minimized. The algorithm consists of the following steps:

(1) Load the calibration data, including the influence line for each sensor.
(2) Calculate the speed of the train using the phase difference method described below in Section 4.1.
(3) Detect the number of axles and make a rough estimate of their position, speed and load.
(4) Adjust the axle positions, axle load and the speed and acceleration of the train to minimize the difference between the calculated and the actual strain curve.

A thorough description of the important steps in the algorithm are described below in the following subsections.

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

The B-WIM algorithm described in the previous section relies on a good initial guess of the train speed. Because this calculation needs to be performed before the actual B-WIM calculation, it must not depend on knowing anything about axle positions etc. One way of doing this is to identify a peak on the strain curve on both sensors U1 and U4 (see Fig. 3), and measure the time difference between the two peaks. This time is the time it takes for the train to travel the distance between the two sensors, from which the speed can be easily calculated. Determining the speed of a train using the method described above relies on identifying a peak which represents the same axle on both sensors U1 and U4. Although this method provides a reasonable first guess, it is difficult to accurately computerize the operation of identifying peaks, since noise may shift the maximum strain measured away from the actual peak. A simpler and more accurate method consists of finding the phase difference between the signals for the two sensors which minimize the difference between the two signals. This can be expressed mathematically as trying to find the value p which maximizes the following equation:

$$\sum_{n=1}^{N-p} \frac{S_{1,n} S_{4,n+p}}{N-p},$$

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

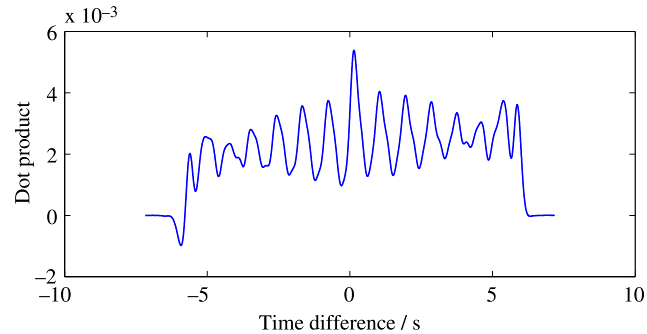

Fig. 4. The difference between the signals varies when a phase difference is introduced.

Fig. 4 shows the result of calculating the above equation for varying p. The highest peak is clearly identifiable, and the p for which it occurs is inversely proportional to the train speed. This method is fast, robust and accurate; furthermore, it does not require any knowledge about the train passing by. The only additional information beside the strain curves which needs to be supplied is a constant, which should theoretically be the distance between the sensors U1 and U4. In practice the influence line for sensors which are not placed at the centre of the bridge will be asymmetrical, which results in a systematic error. Because of this, a calibration run using a train travelling at a known speed is recommended for maximum precision.

4.2. Axle detection

The first step of the actual axle detection consists of making an initial guess of the train properties. The train data consist of information on the number, position and weight of each axle, and the speed and acceleration of the train. The initial guess on train speed is calculated using the phase difference. Given an axle position, a reasonable estimate of the axle load can be obtained by using the measured strain at the time of the axles crossing over the sensor. This leaves us with the problem of detecting the number of axles and their positions. This is difficult since two axles are often too closely spaced to be easily separable. A heuristical algorithm has been developed that uses the following steps:

(1) Identify the peaks of the curve and assume they represent some of the train axles.
(2) Adjust the calculated axle positions, the load and the speed of the train to minimize the difference between the actual measured strain curve from the simulated strain curve.
(3) Calculate an error curve by subtracting the simulated strain curve from the actual measured strain curve.
(4) Identify the peaks of the error curve and assume the highest peak represents an additional train axle.
(5) If no suitable new axle position can be located, break.
(6) Place a new axle at the peak.
(7) Go to step (2).

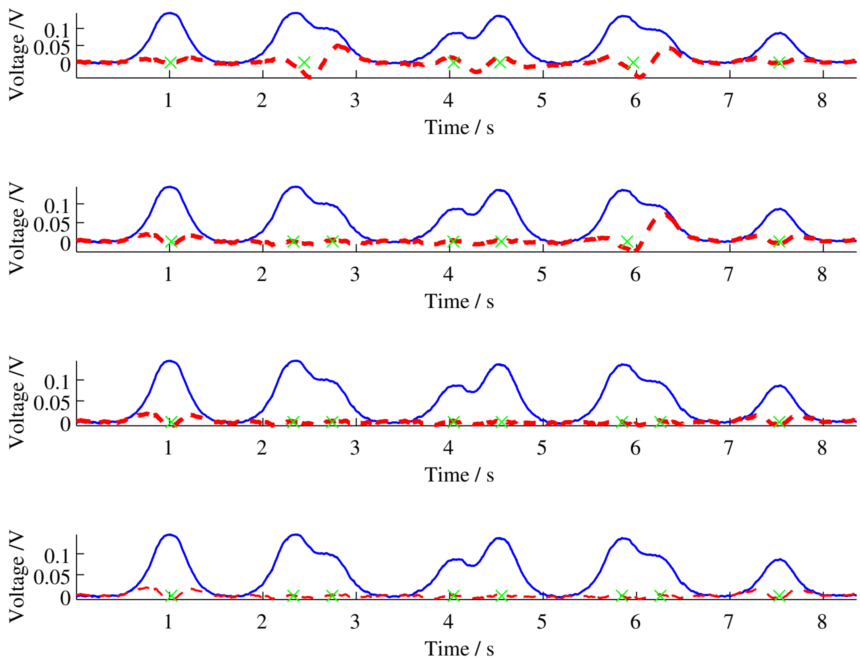

Fig. 5. How additional axles are gradual identification on a commuter train. Only U3, the sensor under the commuter track is shown. The blue line is the measured strain, the red line is the difference between measured and calculated strain and the green crosses are detected axle positions. (For the interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Fig. 5 shows the algorithm at work gradually identifying all axles of a short commuter train. It is important to only add one additional axle at a time, because if a pair of two axles have been identified one axle, the error curve will often contain two peaks in the error curve, one on each side of the one identified axle. Identifying the peaks of a curve is not completely trivial if the curve contains noise. It is advisable to perform the peak identification on an extensively filtered curve.

4.3. Adjusting the train data

After calculating the train speed and axle positions, the only missing variables from a complete estimate of the system properties are axle load and train acceleration. As a rough initial estimate, the axle load can be estimated as 70% of the load at the time the axle crosses the sensor, and the acceleration can be set to 0.

After this initial estimate has been created of the train properties has been made, the guess is adjusted to minimize the difference between the actual measured load curve and the one generated using the train properties. This is a nonlinear optimization problem which can be defined as:

Minimize

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

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

The algorithms described in this paper are implemented in the MATLAB language. Originally, the MATLAB function fminsearch was used to perform the minimization. But since this was found to perform slowly and inaccurately if the initial guess was not extremely accurate, an intermediary step was used. The chosen approach was to find the local minimum along one degree of freedom at a time. The minimization of axle load, speed and acceleration use discreet steps of one percent when adjusting the values, whereas the axles are adjusted one time step at a time. After the train data have been adjusted using the above described minimization function, a call to fminsearch is used to increase the precision. Figs. 6 and 7 show how close the results of the axle detection algorithm match the actual measurements.

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

4.4. Generating the simulated load curve

The simulated load curve is calculated using the influence line of the bridge at each sensor and the load and position of each axle of the train as well as the speed and acceleration of the train.

The contribution of a given axle to the strain at a given sensor is calculated using Moses algorithm [4]. The total

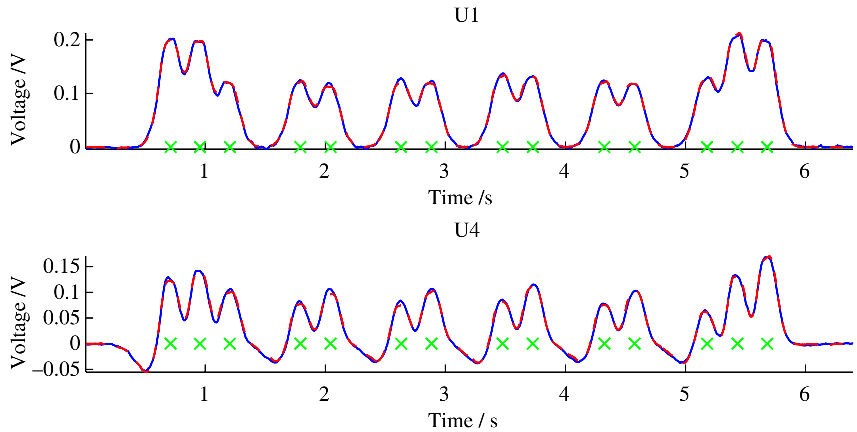

Fig. 6. The measured and simulated strain for a regional train with one locomotive at each end. The plots are for sensors U1 and U4, the blue line is the measured strain, the red line is the calculated strain and the green crosses are detected axle positions. (For the interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

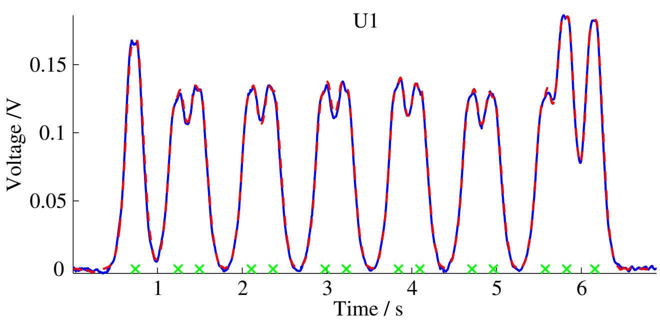

Fig. 7. The measured and simulated strain for a high speed train with one power car at the beginning of the train and one locomotive at the end. The plots are for sensor U1, the blue line is the measured strain, the red line is the calculated strain and the green crosses are detected axle positions. (For the interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

strain curve for a sensor is simply the sum of the strain of each axle. This can be expressed as:

$$L_j(t) = c_j \sum_{k=1}^{N} \bar{i}_j(p(k,t))m(k),$$

where $L_j(t)$ is the strain at the jth sensor, c_j is the calibration constant, $\bar{i}_j(x)$ is the influence line of the jth sensor at position x, $p(k,t)$ is the position of the kth axle at time t, $m(k)$ is the gross weight of the kth axle and N is the number of axles.

4.5. Calibrating the system

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

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

The algorithm will fail if none of the influence lines chosen in the first step match the actual influence line. This has not been found to be a problem on the Årstaberg bridge. Fig. 8 shows the strain curve and the error curve during calibration using a Gauss bell influence line.

The last step of the calibration deserves some elaboration. Moses algorithm was originally used to calculate the axle weight given an influence line. But Quilligan [6] used the algorithm in reverse to calculate the influence line given a known set of axle weights and a strain curve. If all axles of the system are separated, this is a trivial problem. In the real world, bridges are often longer than the axle distance of a wagon, so it cannot be expected that axles are separated from each other in the strain curve. The problem of calculating the influence line $\bar{i}$ of a bridge given a strain curve recording $\bar{r}$ of multiple axles traversing the bridge at known times with known speeds using Moses algorithm can be expressed as a sparse linear equation of T variables, where T is the number of samples in the strain curve. This is done by constructing a matrix A, which is of size $T \times L$, where L is the number of elements in the desired influence line. The element on the nth row and the mth column of A corresponds to the strain at time step n generated by any axle at point m on the influence line. This means that A is a sparse matrix consisting of one diagonal line for each axle of the train. If A is multiplied by a vector representing an influence line $\bar{i}$, this will result in a strain curve. Since we want this strain curve to approximate the measured strain

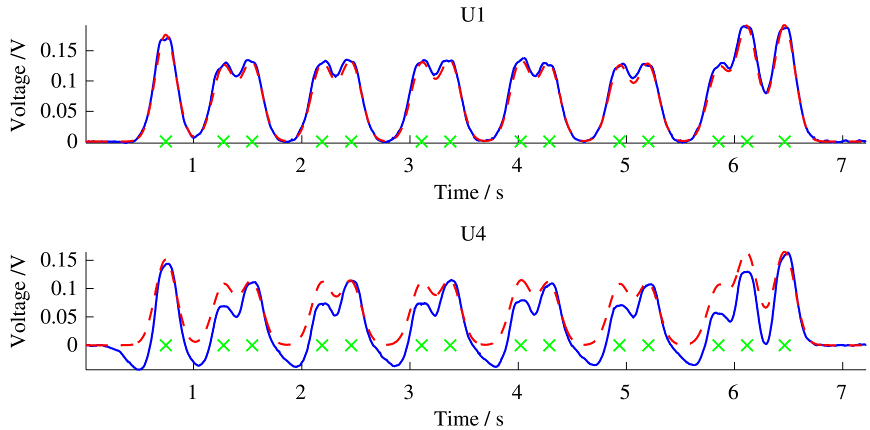

Fig. 8. The measured and generated load curve using a Gaussian bell as an influence line. The plots are for sensors U1 and U4, the blue line is the measured strain, the red line is the calculated strain and the green crosses are detected axle positions. (For the interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

curve, $\bar{r}$, we want to find an influence line $\bar{i}$, which will satisfy the relationship $A\bar{i} = \bar{r}$. Since we can determine the number of samples in our generated influence line, it might seem like a good idea to use $L = T$. This is not the case, since it will usually result in a singular A. Instead one should choose $L \ll T$ and use the least squares minimization of the above system. This will result in an accurate estimate of $\bar{i}$.

The influence lines generated using the above algorithm have a very high accuracy. Fig. 9 shows the influence line generated by seven different sets of trains passing over the Årstaberg Bridge at different speeds. A slight displacement between the influence lines can be seen, but this does not affect the accuracy of the calculations.

4.6. Locomotive identification

The B-WIM algorithm produces estimates of the static axle load and axle distances of all locomotives and wagons passing over the bridge. Given a database of locomotives, this information can be used to identify the locomotive type. If we assume that the errors in mass and speed calculations are independent, and given the standard deviation of the speed and mass calculations (which will be presented later in this article), it is possible to calculate the probability that a given locomotive would give rise to the given output. Given calculated axle distance d_c and mass m_c, known locomotive data from the database d_l and m_l, as well as the standard deviation of the calculation σ_d and σ_m, the probability of the given train giving rise to the calculated output is $p(d_c - d_l, \sigma_d)p(m_c - m_l, \sigma_m)$, where $p(x, \sigma) = e^{-(x/\sigma)^2}$.

4.7. Autocalibration of the system

An algorithm for automatically calibrating the B-WIM system has been developed. After initially calibrating the system using the method described in Section 4.5, each passing train is identified using the method described in Section 4.6. If a locomotive is identified with a high confidence, the calibration values are shifted so as to further decrease the error in the train calculations. In the test system, only c_j, the proportionality constant between the strain sensor output and the bogie gross weight is updated, not the shape of the influence line.

4.8. Determining the speed of the train using a single strain curve

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

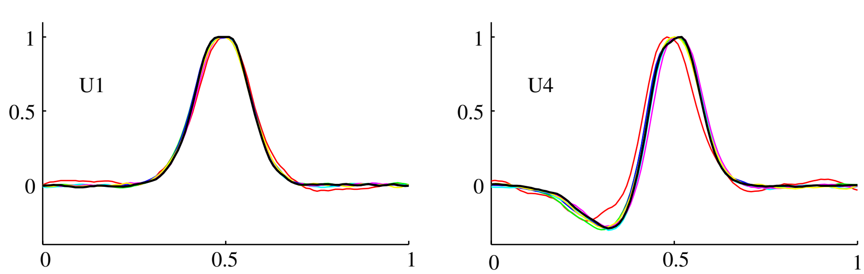

Fig. 9. The influence lines for sensors U1 and U4 generated by calibration using seven different trains.

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

5. Test details

The authors performed a set of measurements on 33 train sets using the four strain sensors, as well as an accelerometer and a laser speed measuring pistol of the same type used by the police. The results of these measurements are presented in Table 1. The speeds of the recorded passing trains (commuter trains, high-speed trains, and regional trains) varied between 38 and 114 km/h. Since there are several different methods to calculate the train speed from the collected sensor signals and it is desirable to know the accuracy of each method, the laser speed pistol was also used to get accurate measurements of the train speeds. The accelerometer data has not been used here, but will be used and presented in future work.

It should be noted that all the commuter trains used the low speed track under which only one sensor was placed and that all other trains used the high speed track under which the remaining three sensors where placed.

Table 1
The data for the recorded train sets

Number	Type	Wagons	Speed (km/h)	Time
1	Commuter	8	52	10:49
2	Commuter	4	53	10:55
3	Regional	6	44	10:57
4	Commuter	4	50	11:00
5	High speed	5	–	11:05
6	Commuter	4	50	11:15
7	Commuter	8	52	11:16
8	Commuter	4	45	11:26
9	Regional	2	102	11:32
10	Commuter	4	50	11:34
11	High speed	7	99	11:39
12	Commuter	4	38	11:40
13	High speed	7	114	11:44
14	Commuter	8	47	11:47
15	Commuter	4	44	11:55
16	Commuter	4	50	12:10
17	Commuter	4	50	12:13
18	Commuter	8	–	12:18
19	Regional	2	–	12:19
20	Commuter	4	–	12:25
21	Regional	4	–	12:32
22	High speed	7	–	12:37
23	Commuter	4	–	12:39
24	Commuter	8	–	12:41
25	High speed	7	–	12:43
26	Commuter	8	–	12:46
27	Regional	5	–	12:56
28	Regional	4	64	13:04
29	Commuter	4	44	13:08
30	Commuter	4	49	13:11
31	Regional	5	114	13:30
32	High speed	7	105	13:32
33	High speed	7	–	13:40

Note that due to technical difficulties not all trains have a measured speed.

6. B-WIM results

The axle detection algorithm described in this article successfully detected every axle of every train passing that was recorded during the course of half a day.

The trains that are used for calibration purposes are of course excluded from the analysis.

There are several means of calculating the speed of the train from the collected data. Fig. 10 shows how the train's speed, calculated using the two different algorithms described in Sections 4.1 and 4.8, varies with its speed as measured by the speed laser pistol (considered here to be the real speed). The average difference between calculated and measured speed is very small and varies depending on which trains are used for calibration. This is not surprising, since the calibration process should remove any systematic error. The standard deviation of the difference between calculated and measured speed is about 5% for both calculation methods. It should be noted that the speed calculations are co-variant which implies that a significant portion of the error comes from the laser pistol. Such errors originate from various sources, including train

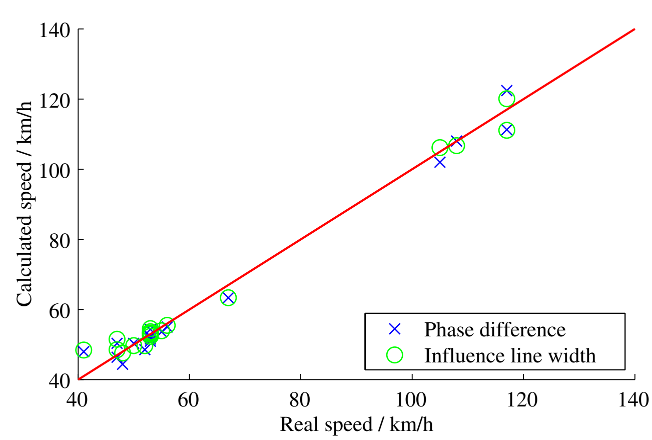

Fig. 10. The measured "real" speed of 13 commuter train sets and 5 regular train sets along the x-axis and the B-WIM calculated speed on the y-axis. Two different methods for calculating the speed were used, these are shown separately.

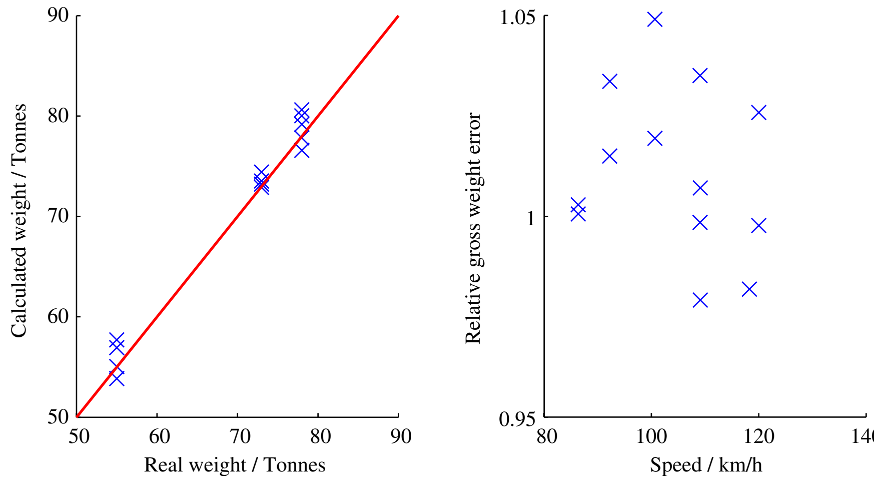

Fig. 11. The variation of calculated gross weight estimate with real gross weight and the variation of gross weight estimate error with speed for 13 locomotives.

acceleration (speed measurements where done about 100 m before the bridge), the pistol not being completely parallel to the train tracks at the time of measuring and other sources of error in the speed pistol.

Fig. 11 shows how the locomotives calculated gross weight varies with its real gross weight. The average error is small and varies between different runs. This is not surprising since the calibration process should remove any systematic errors. The standard deviation of the error in estimated gross weight is approximately 2%. The error in estimated bogie load is approximately 2.5%.

Fig. 11 also shows how the error in the locomotives calculated gross weight varies with the speed of the locomotive. There is no obvious tendency towards speed dependency. It should be noted that the variation in speed between the different locomotives is small, such tendencies might well be noticeable at higher or lower speeds. The speed values used to produce Fig. 11 is the calculated speed, not the speed as measured by the laser pistol. This is because the laser pistol was not used on all of the trains used to produce the figure. It should also be noted that several of the trains used to produce Fig. 11 had more than one locomotive. It is interesting to note that there appears to be a slight co-variation in the error of multiple locomotives in the same train.

The locomotive identification algorithm correctly identified all locomotives. This was not a very difficult task since only three types of locomotives where measured, with significant differences in both mass and axle distance.

7. Conclusions

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

The phase differences of the signals can be used to quickly calculate the speed of a passing train. Using the width of the influence line was found to give a slightly more accurate results.

The bridge instrumentation on the Årstaberg bridge is not sensitive enough to separate the axles of a single bogie. This will probably be the case for most railway bridges used for B-WIM instrumentation. This might cause a problem when wagons using different bogie distance pass over the bridge. In practice, it was found that compensating for this actually decreased the precision of the system, though further research into this might increase the systems precision.

After system calibration, the B-WIM system had very small systematic errors in speed and weight measurements. The standard deviation of the error in speed using the two calculation methods is about 5%. The standard deviation in locomotive gross weight error is about 2% and the standard deviation of the error in bogie weight is about 2.5%.

It is unknown how a large part of the speed calculation error comes from the direct speed measurements using the speed laser pistol. It is noteworthy that the speed calculations performed very well for trains on the commuter track, even though this track only had one sensor underneath it. The information from the sensors placed under the neighboring high speed track provided enough information to accurately complete the phase calculations described in Section 4.1.

The B-WIM system is accurate enough to correctly identify the locomotives that passed over the bridge during measurements.

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

Acknowledgments

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Appendix C

A MATLAB toolbox for real-time evaluation and monitoring of traffic loads on railway bridges

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Twim, A MATLAB toolbox for real-time evaluation and monitoring of traffic loads on railway bridges

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(*Revsion received 00 Month 200x*)

This paper describes Twim, a toolbox written in the MATLAB computer language. Twim is designed for monitoring bridge behavior during train passages as well as for performing Bridge Weigh-In-Motion of railway traffic, both in real-time and offline. The algorithms calculate the static bogie loads and bogie distances, as well as the speed and acceleration of the train. Twim also includes visualization functions, automatic identification of known locomotives and an auto-calibration that uses locomotives with known bogie loads. The algorithms used place specific requirements on both the bridge type and the instrumentation of the bridge. These requirements are explained in the paper. The instrumentation of several bridges is described, and some of the interesting results gained through this instrumentation are presented.

1 Introduction

Until recently, most of the research in the area of bridge design has concentrated on the study of the strength of materials and relatively few studies have been performed on assessing actual traffic loads and their effects on bridges. As a result, the correctness of the traffic loads, current safety factors and dynamic amplification factors used today by bridge engineers for design and assessment of bridges can be questioned (James 2003). It is widely known that high axle loads lead to bridge deterioration and eventually increasing maintenance costs and decreasing service life of bridge structures. Consequently, within the bridge engineering community, there is today a considerable interest in the problem of measuring actual traffic loads and their dynamic effects on bridges.

In Sweden, several bridges have recently been instrumented by the authors, where strain transducers were placed on the soffit of the bridge or embedded in the bridge deck section. This relatively inexpensive instrumentation makes it possible to:

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

This article describes Twim, a toolbox written by the authors and designed to make it easy to perform B-WIM calculations. The toolbox contains a small number of functions written in the MATLAB programming language, designed to perform B-WIM calculations on any suitably instrumented bridge. The instrumentation requirements, the algorithms behind Twim, how to use the different parts of the toolbox, and some results from B-WIM calculations using Twim are presented in this article.

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2 Instrumentation and the BRAVE data acquisition system

The B-WIM system described in this paper requires a minimum of two sensors, preferably strain transducers, installed on the soffit of the bridge slab/beam or may be embedded in the concrete section. Increasing the number of sensors will of course result in increased accuracy of the system, especially for bridges with more than one railway track. At least two of the sensors must be installed a distance apart in the longitudinal bridge axis as this will enable the evaluation of train speeds, travelling directions and bogie distances.

The thickness of the track slab/beam and the ballast will naturally determine if individual axles or only bogies can be identified. In order to achieve accurate estimations of speed and axle/bogie position, the individual axles/bogies should be clearly distinguished in the measured signals. The more local effect the sensors measure the more accurate the speed and position estimates will be, which in turn is important for the accuracy of the load calculations as well.

On the other hand, the more local the effect the sensor measure, the larger the error caused by dynamic effects will be. The latter effect comes from the fact that low frequency (1-2 Hz) dynamic response can often be as large as 20% of the static response. To remove this effect, one needs to measure at least one whole cycle of oscillation, which means measuring over a very long distance when trains travel at a speed of well over 100 km/h. (Quilligan 2003). This conflict of interest with regards to locality of influence when performing axle detection and when weighing individual axles is a potential problem with B-WIM calculations. An ideal B-WIM system would contain both sensors that measure very local effect for axle identification and sensors that measure a global effect to remove dynamic components from the system.

If the bridge is a single span rigid structure such as an integral bridge (Figure 3), the sensors can be installed to measure the longitudinal effect of passing trains. However, for multi-span (1) and for flexible bridge structures, such as composite bridges (2), the sensors must be installed to measure the transverse effect of passing trains.

As a train passes over the bridge, a sufficient number of readings are needed for the B-WIM calculations. When performing the phase based speed calculations, as mentioned in subsection 3.1.2, the precision is limited by the fact that the phase difference can only be a whole number of samples. This limits the precision of the calculations to

$$E > \frac{\Delta t v}{l}$$

where E is the relative error, Δt is the time step between samples, l is the distance between the sensors and v is the speed of the train. The speed calculation algorithm has a precision of less than 1%, so a sampling rate of $100v/l$ should be sufficient. At the same time there is little use for a sampling rate of more than 500 Hz as this will give too much dynamics in the signal.

For this study, the following three instrumented railway bridges in Sweden have been used with success for weighing of passing trains and evaluation of the B-WIM toolbox:

Bridge 1) The New Årsta Railway Bridge in Stockholm, opened for traffic in August 2005. This is a complex eleven span pre-stressed concrete structure carrying two unballasted tracks (Figure 1). Two of the 78 meters long spans are instrumented with a total of 40 fiber optic sensors, 21 strain transducers, 6 accelerometers and 9 thermocouples, all embedded in the concrete section. (Wiberg 2006)

Bridge 2) The Skidträsk Bridge in Norrland (Northern part of Sweden) is a 36 m long simply supported composite bridge (Figure 2) carrying one ballasted track. The bridge is instrumented with 4 strain gauges mounted on the two main steel beams to monitor longitudinal strains, 3 accelerometers on the two main steel beams to monitor vertical deck accelerations, 2 B-WIM strain transducers mounted on the soffit of the track slab to monitor transverse strain and one air temperature sensor.

Bridge 3) The Årstaberg Bridge in Stockholm is a concrete integral bridge (Figure 3) with 14.4 m span. The bridge carries two ballasted railway tracks for traffic heading towards the city of Stockholm. The bridge deck supporting the tracks is 0.8 m to 1.3 m thick and is continuously connected to the 0.9 m thick sidewalls. The bridge was instrumented in 2003 by embedding 4 strain transducers to monitor strains in the longitudinal direction. 3 of the transducers are mounted at mid-span and 1 about 3.3 m from mid-span.

Figure 1. The New Årsta bridge during construction.

Figure 2. The Skidträsk bridge.

More information about this bridge and the installed system can be found in Karoumi et al. (2005).

The data acquisition systems for the three bridges is designed and delivered by KTH (Royal Institute of Technology in Stockholm). The system used is the MGCplus (Bridge 1) and Spider8 (Bridge 2 & 3) both from Hottinger Baldwin Messtechnik (HBM).

For Bridge 1, the data acquisition system is connected to the outside world through Internet cable and therefore can be controlled and programmed from the office at KTH. Consequently, real time collection of data, data storage and further processing of recorded data is made using computer facilities at KTH.

Figure 3. The instrumented integral bridge at Årstaberg.

In the case of Bridge 2 and 3, the data acquisition system is connected to a portable computer at site. This computer is connected to KTH using the Swedish wireless MobiSIR system which is a GSM based communication system owned by Banverket (the authority responsible for rail traffic in Sweden). All data logging, data processing and data storage is made on this computer at site and only interesting data and result files are transferred to KTH. To connect, remotely manage and for operational control of these site computers and of the data acquisition systems, the software pcAnywhere™ from Symantec is used.

The Catman® based BRAVE software (BRidge Automatic Vibration Evaluation) developed by KTH for real time data collection, data processing and data storage is used in this study. The selected logging procedure in BRAVE provides continuous sampling of data. Here 600 Hz with a low pass Bessel filter set at 15% of sampling rate is chosen. Only raw data files containing interesting train passages are stored. What interesting train passages are is defined by the user by entering trigger levels in BRAVE. The software will then automatically log train passages in separate files having file names that identifies the date and time for each train passage. As large amount of data is collected, it is important, especially for Bridge 2 and 3, that as much signal analysis as possible is carried out at site. BRAVE is developed for this purpose and has shown to work very effectively. Apart from being able to collect train passages in separate files, the BRAVE software calculates statistical data such as mean, maximum, minimum and standard deviation for each sensor and stores it in a statistical data file. The time interval between such calculations is defined by the user.

Twim, the MATLAB toolbox described in this paper, can be used to search continuously after new files with train passages. As soon as such a file is stored by BRAVE, the B-WIM toolbox starts analyzing the data using the procedures described in the following section. For each collected train passage, results such as time for passage, identified train type, speed, direction, number of bogies, bogie distances and most importantly static bogie loads are stored in one file per day. Apart from that, statistical information for each day, such as maximum measured train speed, maximum measured bogie load, maximum bridge deck acceleration and maximum strain is stored in another file.

3 Description of Twim, the B-WIM toolbox

This section consists of two subsections. Subsection 3.1 gives a brief overview of how the Twim toolkit works internally, and section 3.2 describes the components of the Twim toolbox and how to use them.

3.1 *Algorithms*

What follows is an outline of the internal algorithms used by the B-WIM functions in the toolbox described in this article. For a more complete description, see Liljencrantz et al. (Accepted for publication in 2006).

The basis of the WIM algorithm described in this article is that given a train consisting of a set of bogies with a specific load, speed, acceleration and internal distance, as well as the influence line of the bridge at several sensor positions, an accurate simulated strain curve can be calculated for the train passage. By repeatedly comparing the simulated strain curve with the measured one, and adjusting the train data, one will eventually produce an accurate simulated strain curve.

The resolution of the B-WIM algorithm depends on the bridge type and if the track is ballasted or not. For most bridges, the individual axles of a bogie can not be separated. Consequently, for such bridges the B-WIM algorithm incorrectly identifies bogies as axles. This has not been found to decrease the algorithm's efficiency, even with varying internal bogie axle distance. In fact, attempts to compensate for varying bogie axle distance were found to slightly decrease the accuracy of the results.

3.1.1 ***An initial guess.*** The first step of the WIM calculations consists of making an initial guess of the train properties. The train data consists of information on the number, position and load of each bogie, and the speed and acceleration of the train. The initial guess on train speed is calculated using a phase difference method described below. An initial guess on the number of bogies and bogie distances can be made by identifying all peaks in the signal, and removing any peaks that are too closely spaced or of insufficient amplitude. Given a bogie position, a reasonable estimate of the bogie load can be obtained by using the measured strain at the time of the bogies crossing over the sensor.

3.1.2 ***Determining the speed of the train using the phase difference between signals.*** The B-WIM algorithm needs to make a semi-accurate initial guess about the system to start out with. Specifically, an estimate of the speed of the system is very valuable. Because this calculation needs to be performed before the actual B-WIM calculation, it must not depend on knowing anything about bogie positions etc.

To make this initial estimate, the WIM algorithm described in this article needs two strain curves, taken from sensors placed a known distance from each other. The exact method used is described in Liljencrantz et al. (Accepted for publication in 2006).

3.1.3 ***The main loop.*** The main loop of the WIM algorithm uses the following steps:

(1) Adjust the calculated bogie positions, the load and the speed of the train to minimize the difference between the measured strain curve from the simulated strain curve.
(2) Calculate an error curve by subtracting the simulated strain curve from the measured strain curve.
(3) Identify the peaks of the error curve and assume the highest peak represents an additional train bogie.
(4) If no suitable new bogie position can be located, break.
(5) Place a new bogie at the peak.
(6) Go to step (1).

These steps are described in more detail in the following sections. Figure 4 shows the algorithm at work gradually identifying all bogies of a short commuter train. It is important to only add one additional bogie at a time, because if a pair of two bogies have been identified as a single bogie, the error curve will often contain two peaks, one on each side of the one identified bogie. Identifying the peaks of a curve is not completely trivial if the curve contains noise, therefore it is advisable to perform the peak identification on an filtered curve. Great care must be taken when filtering, since many filtering algorithms slightly alter the phase of the signal. A low order butterworth filter has been found to give good results.

3.1.4 ***Generating the simulated load curve.*** Given the measured influence line of the bridge at each sensor position, the number and relative distances of all bogies, as well as their load, and the speed and

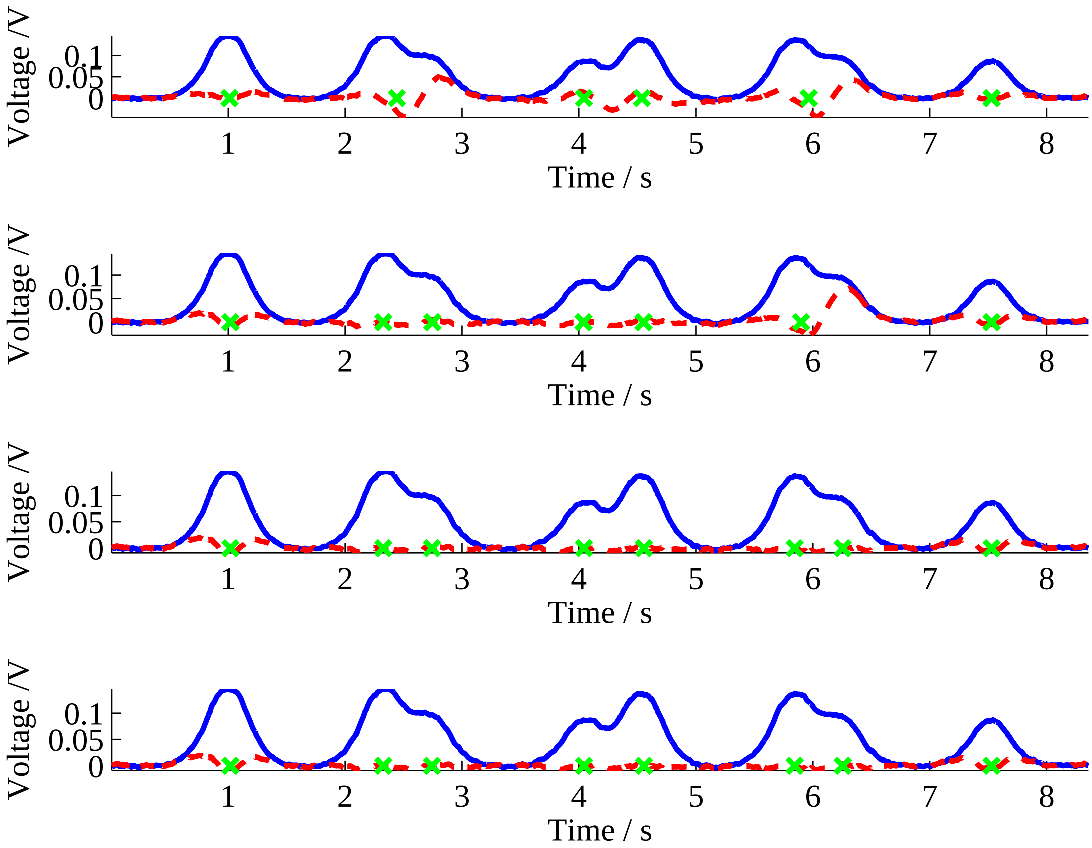

Figure 4. shows how additional bogies are gradually identified on a commuter train on the Årstaberg bridge. The blue line is the measured strain, the red line is the difference between measured and calculated strain and the green crosses are detected bogie positions.

acceleration of the train, a simulated strain curve can be calculated for a specific train passage.

The contribution of a given bogie at a specific point in time to the strain at a given sensor is calculated using Moses algorithm (Moses 1979). The total strain curve for a sensor is simply the sum of the strain of each axle (or in this case bogie). This can be expressed as:

$$L_j(t) = c_j \sum_{k=1}^{N} \bar{i}_j \Big(p(k,t) \Big) \, m(k),$$

where $L_j(t)$ is the strain at the j:th sensor, c_j is the calibration constant, $\bar{i}_j(x)$ is the influence ordinate of the j:th sensor at the bogie position x, $p(k,t)$ is the position of the k:th axle at time t, $m(k)$ is the load of the k:th bogie and N is the number of bogies.

This method does of course not take into account any dynamic effects, but other than that, the simulated strain curve should be reasonably accurate. The fact that the generated curve is essentially a static response curve means that it is possible to approximate the dynamic response and the dynamic amplification factor by simply examining the difference between calculated and measured signal.

3.1.5 ***Adjusting the train data.*** After the initial guess of the train properties has been made, the guess is adjusted to minimize the difference between the measured strain curve and a simulated one. This is a non-linear optimization problem which can be defined as:
Minimize

$$O(y) = \sum \Big(\, L_c(y) - L_m \Big)^2$$

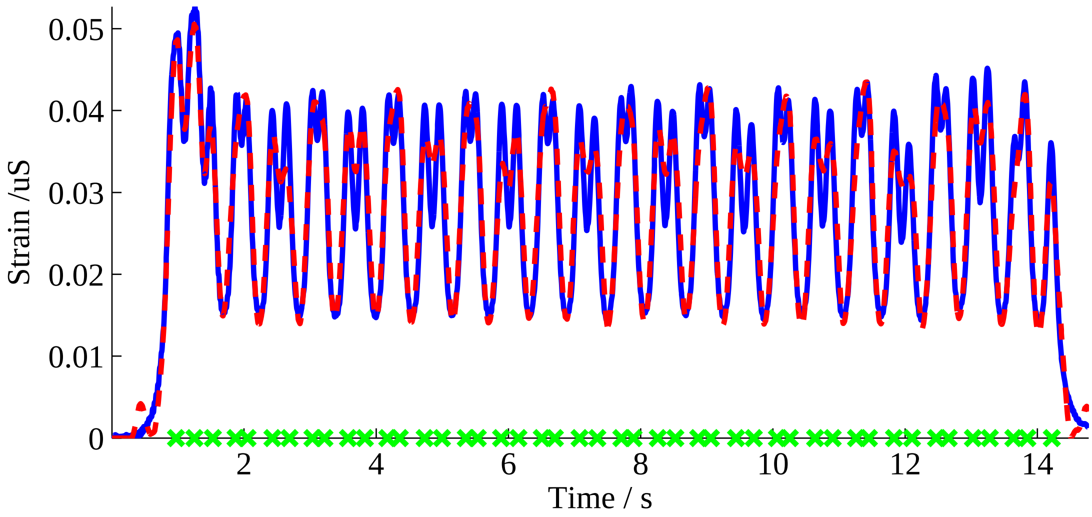

Figure 5. The measured and simulated strains for a regional train with one locomotive at the front passing over the Skidträsk bridge. The blue line is the measured strain, the red line is the calculated strain and the green crosses are detected bogie positions.

to find $y = \{v, a, p_1, p_2, \ldots, p_N, m_1, m_2, \ldots, m_N\}$ where $O(y)$ is the objective function, v and a are the speed and acceleration of the train, p_n and m_n are the position and load of the n:the bogie, $L_c(y)$ is a function that generates a load curve given a set of train properties as described in section 3.1.4, and L_m is the measured load curve.

3.1.6 ***Calibrating the system.*** System calibration is performed automatically using locomotives from regular crossing traffic. The only user input that is needed is the total load and the bogie distance of a locomotive or other common and easily identified wagon with a known weight and bogie distance. The calibration consists of the following steps:

(i) Make an initial guess on the appearance of the bridges influence line at each sensor position. Several guesses could be made using different functions to generate the influence line, but in practice a gauss bell has provided excellent results.
(ii) Perform a regular bogie detection using this guessed influence line.
(iii) Find the influence line that minimizes the least squares difference between the measured strain curve and the strain curve generated using the train data.
(iv) Calculate the proportionality constants between static bogie load and strain sensor voltage, c_j, as described in section 3.1.4. For this step, it is obviously necessary to know the bogie loads of the locomotive.
(v) Calculate the proportionality constant for the train speed calculation by using the time difference between bogie crossings and the bogie distance of the locomotive.

The algorithm will fail if none of the influence lines chosen in the first step match the actual influence line. This has not been found to be a problem on any of the bridges that have been tested.

The last step of the calibration deserves some elaboration. Moses algorithm was originally used to calculate the bogie load given an influence line. But Quilligan (2003) used the algorithm in reverse to calculate the influence line given a known set of bogie loads and a strain curve. If all bogies of the system are separated, this is a trivial problem. In the real world bridges are often longer than the bogie distance of a wagon, so it can not be expected that bogies are separated from each other in the strain curve. The problem of calculating the influence line $\bar{i}$ of a bridge given a strain curve recording $\bar{r}$ of multiple bogies traversing the bridge at known times with known speeds using Moses algorithm can be expressed as a sparse linear equation of T variables, where T is the number of samples in the strain curve. This is done by constructing a matrix A, which is of size $T \times L$, where L is the number of elements in the desired influence line. The element on the n:th row and the m:th column of A corresponds to the strain at time step n generated by any bogie at point m on the influence line. This means that A is a sparse matrix consisting of one diagonal line for each bogie of the train. If A is multiplied by a vector representing an influence line $\bar{i}$, this will result in a strain curve. Since we want this strain curve to approximate the measured strain curve, $\bar{r}$, we want to find an influence line $\bar{i}$, which will satisfy the relationship $A\bar{i} = \bar{r}$. Since we can determine the number of samples in our generated influence line, it might seem like a good idea to use $L = T$. This is not the case, since it will usually result in a singular A. Instead one should choose $L \ll T$ and use the least squares minimization of the above system. This will result in an accurate estimate of $\bar{i}$.

3.1.7 ***Locomotive identification.*** The B-WIM algorithm produces, among other things, estimates of the static bogie load and bogie distances of all locomotives and wagons passing over the bridge. Given a database of locomotives, this information can be used to attempt to identify the locomotive type. The basic assumptions made are described in more detail in Liljencrantz et al. (Accepted for publication in 2006).

3.1.8 ***Autocalibration of the system.*** An algorithm for automatically calibrating the B-WIM system has been developed. After initially calibrating the system using the method described in section 3.1.6, each passing train is identified using the method described in section 3.1.7. If a locomotive is identified with a high confidence, the calibration values are shifted so as to further decrease the error in the train calculations. In the test system, only c_j, the proportionality constant between the strain sensor output and the bogie load is updated, not the shape of the influence line.

3.2 *Twim layout*

Twim is designed to provide users who are vaguely familiar with MATLAB with a powerful set of WIM-tools that allows them to perform advanced calculations without special training. To that end, the toolbox has a small number of functions that perform well defined tasks. Several of the WIM functions take a special structure representing a train passage as an argument. This structure must contain the following fields:

- strain, an array representing the strain curves
- best_channel, the primary channel for the speed calculation
- second_channel, the secondary channel for the speed calculation

3.2.1 ***Calibration.*** To calibrate the system, he wim_calibrate function is used. This function takes a train passage structure, as described above, but containing the following additional fields:

- dt, the time step
- real_speed, the speed of the train (optional)
- dist, the distance between the sensors
- real_weight1 the load of the first wagon of the train (optional)
- real_weight2 the load of the last wagon of the train (optional)
- real_dist1 the bogie distance between the first two bogies of the train (optional)
- real_dist2 the bogie distance between the last two bogies of the train (optional).

At least one of real_weight1 and real_weight2 must be supplied in order to calibrate the load calculations. At least one of real_speed, real_dist1 and real_dist2 must be supplied in order to calibrate the speed calculations. wim_calibrate returns the calibration data for the bridge.

The calibration function will perform a B-WIM calibration using a Gauss bell influence line, and use the resulting set of bogies and bogie loads and the matrix method described earlier in this article to correctly calculate the influence line of the system. Afterwards, the speed and load calibration values are calculated, and all such parameters are returned.

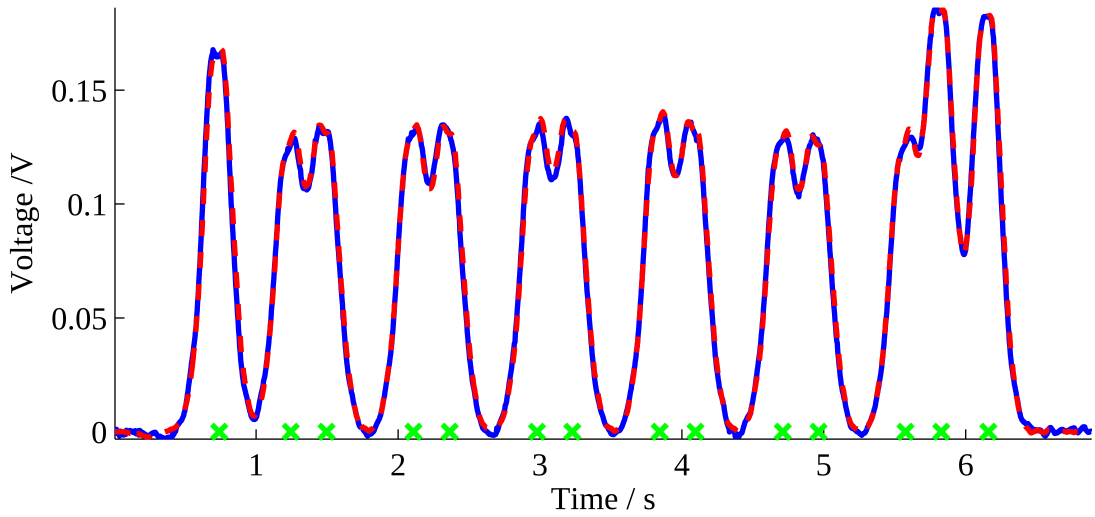

Figure 6. An example of the output from the wim_plot_result function. The measured and simulated strain for a high speed train on the Årstaberg bridge with one power car at the beginning of the train and one locomotive at the end. The blue line is the measured strain, the dashed red line is the calculated strain and the green crosses are detected bogie positions.

3.2.2 ***Regular detection.*** To perform WIM calculations on a train passage, the wim_calculate function is used. It takes two arguments, a train passage and calibration data as returned by wim_calibrate.

wim_calculate uses the influence line calculated by wim_calibrate to perform the B-WIM detection described in earlier sections of this article. Afterwards, the calibration factors are applied and the result is returned.

wim_calculate returns a structure containing the following fields:

- residual, the difference between the simulated strain from the calculated train passage and the real strain curve
- error, the average of the error (i.e. the difference between the real and simulated strain curve), given in the same unit of load used to calibrate the system, usually tonnes
- axles, a listing of all bogie positions
- axle_weight, an array containing the calculated load of each bogie.

3.2.3 ***Result visualization.*** To plot the results of a WIM calculation, the wim_plot_result function is used. It takes the result of a call to wim_calculate as a parameter. The user may optionally also specify a filename where the plot should be saved and an array of channels to show in the plot. By default, all channels are plotted. Figure 6 is an example of the output of the wim_plot_result function. All detection plots in this article are made using the wim_plot_result code.

3.2.4 ***Locomotive identification.*** To identify any locomotives in a train, the wim_identify function is used. It takes the result of a call to wim_calculate as it's first parameter and an array of structures containing the following fields as the second parameter:

- name, the name for this type of locomotive
- mass, the total mass of the locomotive
- axle_dist, the centrum distance between the bogies of the locomotive.

3.2.5 ***Realtime loop function for use with BRAVE.*** The above functions are designed to be easy to integrate with measurements performed in any system that can export it's data to a format that can be

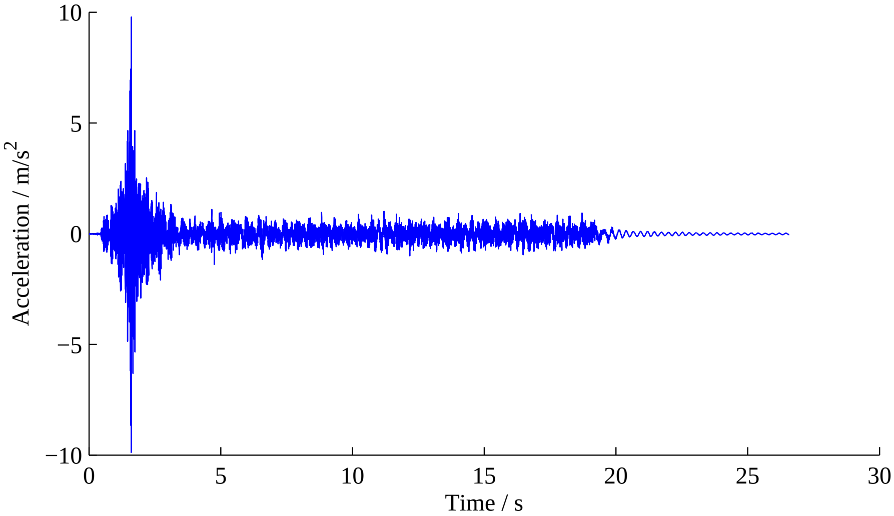

Figure 7. A plot of the highest vertical bridge deck acceleration measured at the midspan of the eastern steel beam on the Skidträsk bridge.

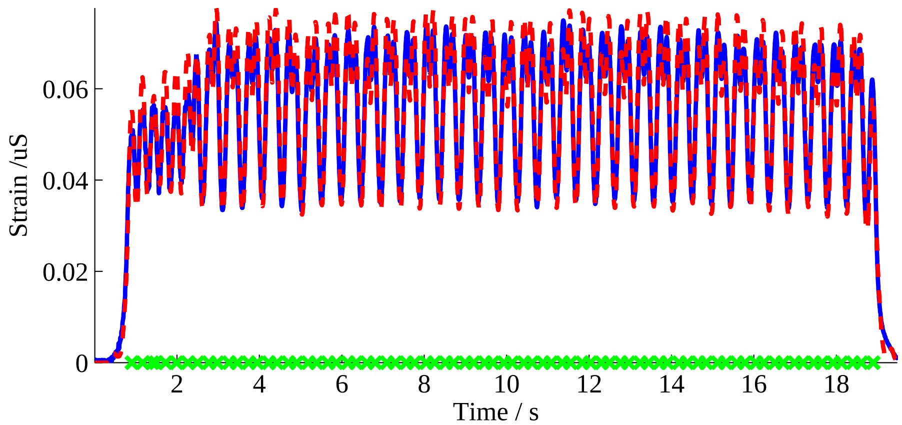

Figure 8. The strain curve for the train giving the maximum vertical bridge deck acceleration on the Skidträsk bridge (Same as in figure 7). The blue line is the measured strain, the red line is calculated strain and the green crosses are detected bogie positions.

parsed by the MATLAB language.

As an example, the toolkit includes wim_do_loop, a main loop that reads the BIN disk format produced by the Catman program, as produced by e.g. the BRAVE program described in section 2. The wim_do_loop function interactively asks the user a number of questions about file locations, bridge data, suitable channels, etc. and then continually scans a directory for new files. New files are then subjected to the B-WIM calculations using wim_calculate, and summary information about all train passages is logged.

4 Results

The Skidträsk bridge in northern Sweden was continually monitored during the course of several days. During this time 113 train passages were recorded. Some of these were false positives, broken recordings or otherwise discarded, leaving 85 passages on which the B-WIM algorithm was used.

The three trains which resulted in the highest detected bogie loads recorded during these passages had bogie loads of 57, 56 and 54 tonnes. The highest train speeds were 161, 154 and 147 km/h. The highest vertical bridge deck accelerations were 9.9, 9.6 and 9.2 m/s^2.

Figures 7 and 8 show the train that had the highest detected vertical bridge deck acceleration. This train is the swedish “Steel arrow” iron ore train pulled by three RC4 engines.

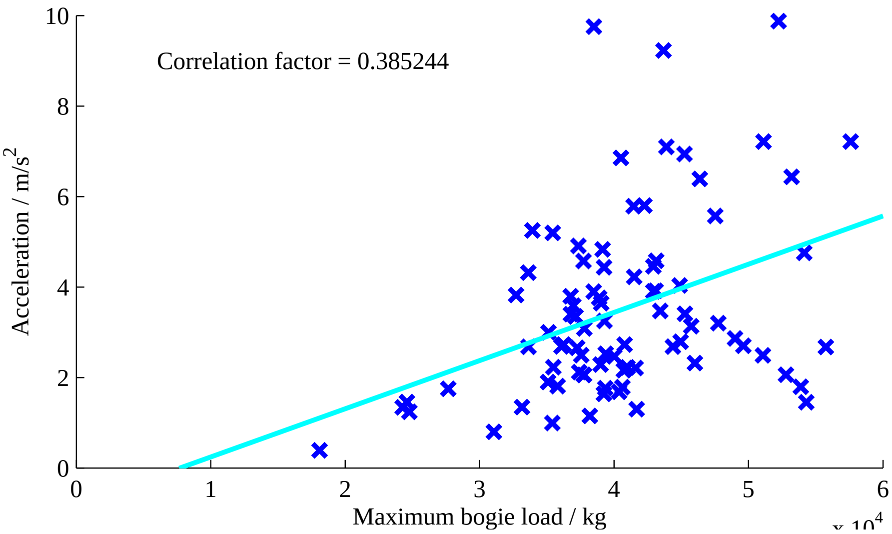

Figure 9. The correlation between the maximum bogie load and maximum vertical bridge deck acceleration measured at the midspan of the eastern steel beam during 85 train passages at the Skidträsk bridge.

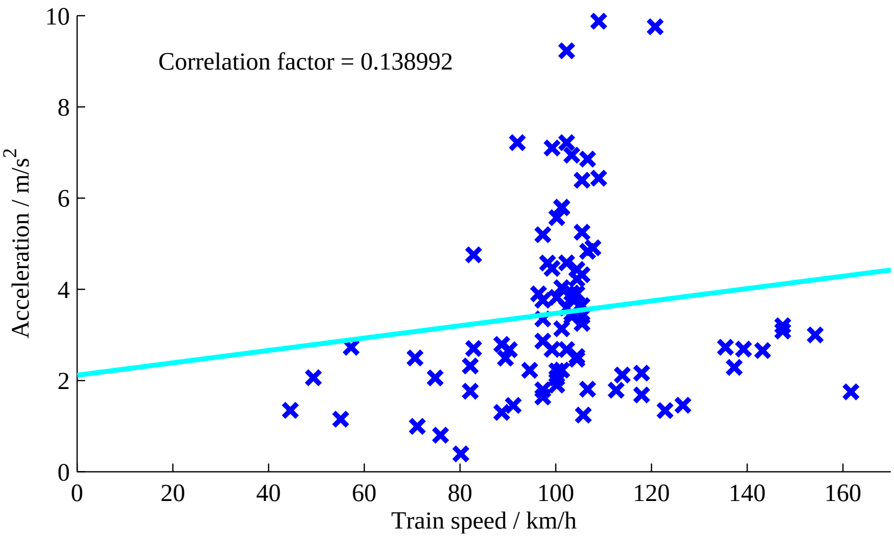

Figure 10. The correlation between train speed and maximum vertical bridge deck acceleration measured at the midspan of the eastern steel beam during 85 train passages at the Skidträsk bridge.

4.1 *Effect of load and speed on bridge acceleration*

The weight and speed of a passing train greatly effects the bridge dynamic behavior, such as the maximum acceleration of the bridge. Figures 9 and 10 show the correlation between maximum bogie load and vertical bridge deck acceleration and the correlation between speed and vertical bridge deck acceleration, respectively. As can be seen from these figures, there is a positive correlation between maximum acceleration and maximum bogie load, and a somewhat weaker correlation between maximum acceleration and train speed. It should be remembered that cargo trains with high load usually travel at slower speeds than lightly loaded passenger trains. The results indicate that for the registered speed interval, the train mass is more critical than the train speed for the maximum vertical acceleration of the bridge deck.

5 Conclusion

The toolbox described in this article has so far been used on three different bridges, and have provided accurate results in all cases. We conclude that the described software is suitable for instrumenting bridges for B-WIM purposes. The sensors can also provide valuable insight on the dynamic properties of the bridge.

Future topics for research include:

- Investigate if the accuracy of the system can be increased by combining sensors measuring local behaviour and sensors measuring global behaviour, in order to better compensate for dynamic effects.
- Investigate how much the accuracy of the system decreases when measuring wagons with only two axles, and if they can be separated from regular bogies.
- Investigate long term changes in the dynamic properties of the instrumented bridges.
- Investigate how the properties of the bridge change between seasons. Specifically, how does the damping properties of the bridge change when the ballast is frozen.
- Investigate how well the autocalibration system handles variations in sensor sensitivity due to temperature changes.
- Investigate what types of bridges can be used to give accurate B-WIM results.

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