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Standardised Bridge Weigh-in-Motion data and its applications in bridge engineering

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Tiivistelmä

Eurokoodin mukaiset siltojen väsytyskuormakaaviot on pääosin kalibroitu keskieuropalaisen liikenteen mukaisesti. Nämä liikennemallit eroavat huomattavasti tyypillisestä suomalaisesta liikenteestä, minkä vuoksi Eurokoodin mukaisella liikenteellä ja todellisella liikenteellä lasketut väsymisvauriot saattavat erota huomattavasti toisistaan. Mitattujen liikennetietojen avulla onkin mahdollista saada tarkempia arvioita todellisista väsytysvaurioista siltarakenteissa.

Weigh-in-Motion (WIM) mittaukset ovat hyvä keino tutkia todellista liikennettä tieosuudella ja kerätä siitä tietoa. WIM-mittausmenetelmiä on monenlaisia, joista silta-WIM (B-WIM) on siltasuunnittelun kannalta yksi parhaiten soveltuva menetelmä. Sen lisäksi, että B-WIM-mittauksilla voidaan tuottaa dataa todellisesta liikenteestä sillalla, pystytään sillä myös mittaamaan siltarakenteen ominaisuuksia ja käyttäytymistä. B-WIM mittauksille onkin olemassa monia hyödyllisiä sovellutuksia ja analysointitekniikoita, jotka voisivat olla tehokkaita ja käytännöllisiä työkaluja siltasuunnittelussa. Datan hyödyntämistä kuitenkin rajoittaa se, ettei sillä ole laajassa käytössä olevaa standardia, joka määrittäisi B-WIM-datan esitysmuotoilua. Tämä vaikeuttaa datan lataamista erinäisiin analysointiohjelmiin ja tekee datan hyödyntämisestä työlästä.

Tämän työn päämääränä on ehdottaa uutta esitysmuotoa B-WIM-datalle, jotta tulevaisuudessa B-WIM-datan hyödyntäminen erilaissa ohjelmistoissa olisi helppoa ja vaivatonta. Tämä mahdollistaisi monien eri mittauspisteiden yhtäaikaisen ja nopean analysoinnin, jonka avulla olisi esimerkiksi helppo vertailla eri tieosuuksien liikennevirtoja ja niistä aiheutuvia seuraamuksia siltarakenteissa.

Lisäksi työssä suoritetaan väsymisanalyysi ortotrooppi kantiselle avattavalle sillalle, hyödyntäen suomalaista B-WIM-dataa. Datalla laskemista varten kehitetään väsymislaskentaohjelma Python-ohjelmointikielellä. Analyysissä vertaillaan B-WIM-datalla saatuja vaurioarvoja Eurokoodin väsymiskuormakaavio 4:n (FLM4) kanssa. Tämän lisäksi tutkitaan vuonna 2013 voimaan tulleen ajoneuvolainsäädännön vaikeuksia hyödyntämällä uudistuksen jälkeen mitattua B-WIM dataa sekä työssä kehitettävää väsymislaskentaohjelmaa.

Avainsanat B-WIM; WIM; Väsyminen; Liikennedata; Liikennekuormat; Terässilta; Ortotrooppinen kansi; FLM4, Avatta silta

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Abstract

As the fatigue load models in the Eurocode were developed based on the central European traffic, in some cases fatigue damage obtained with them may differ greatly from damage calculated with actual Finnish traffic loads. Applying actual traffic data in fatigue analysis can provide more accurate results compared to the ones obtained according to the Eurocode traffic models.

Weigh-in-Motion (WIM) measurements are an excellent tool to produce such traffic data. Among the different WIM methods, Bridge Weigh-in-Motion (B-WIM) is one of the most suitable ones for bridge engineering as it offers an efficient way to measure the traffic flow and it can also offer structural information of the measured bridge. This enables multiple different applications for B-WIM data in the field of bridge engineering. Using B-WIM data as part of the bridge designing process has large potential, but the lack of standardised data format hinders broader utilisation of it. This study proposes a new standardised format to present the measured B-WIM data so that in the future, programs can directly utilise any available B-WIM data. This makes calculations with multiple different traffic compositions and traffic types easy and enables the basis for further utilisation of B-WIM data in bridge designing.

In addition, a fatigue case study is conducted for an orthotropic bridge deck by utilising the Finnish B-WIM data. In the study, multiple different B-WIM measurements with varying traffic compositions are used to calculate the fatigue damage, and obtained results are compared with the damage calculated according to Eurocode fatigue load model 4 (FML 4). To calculate fatigue damage with B-WIM data, a new fatigue calculation software is developed with Python programming language. Additionally, the effects of new traffic regulations set in 2013 are studied by utilising B-WIM data, what are measured after these new regulations, in the fatigue calculation software.

Keywords B-WIM; WIM; Fatigue; traffic data; traffic loads; bridges; Fatigue load model 4

Preface

The idea for this thesis came from Finnish Transport Infrastructure Agency who wanted to further improve their knowledge from Bridge Weigh-in-Motion technology and create a basis for the future development of it. The thesis was done as a collaboration with Finnish Transport Infrastructure Agency and Sweco Structure ltd, who also funded the thesis. I am grateful for both parties on giving me the opportunity and means to write this thesis. Writing of it has been both interesting, but at the same time, a challenging process in both academical and personal sense. Therefore, the people who have been involved in the making of this thesis and those who have been as my moral support deserves my greatest gratitude.

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I am grateful for my partner, family, and friends, on supporting me mentally throughout the thesis, and even in amidst the global COVID-19 pandemic, managed to cheer me up when I felt down. Especially I want to thank my partner Saana on understanding my fatigue and being there for me when I most needed it.

Espoo 25.12.2020

A handwritten signature in black ink, appearing to be 'Jami Qvisén', written in a cursive style.

Jami Qvisén

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List of symbols

A_i	[kN]	i :th axle mass
A_i	[m]	axle spacing (SiWIM format)
A_{GVW}	[kN]	gross vehicle weight
D_L		damage accumulation
D_i	[m]	spacing between axles
D_{TOT}	[m]	total axle spacing
E		error function
E	[MPa]	elastic modulus
G		number of strain gauges
I_i		influence ordinate at i :th axle
M	[kNm]	moment
M_k^m	[kNm]	measured moment on k :th timestep
M_k^t	[kNm]	theoretical moment on k :th timestep
N		number of axles in vehicle
N		number of cycles
T		total number of timesteps
T		temperature
W_{GV}	[kN]	gross vehicle weight (SiWIM format)
W_i	[kN]	axle weight (SiWIM format)
W_i	[m ³]	section modulus of the i th girder/section
f	[Hz]	scanning frequency
n_i		number of cycles associated with certain stress range
v	[m/s]	vehicle speed
β		reliability index value
γ_{Ff}		partial fatigue safety factor
γ_{Mf}		material safety factor
δ		confidence interval width
δ_{min}		minimum allowed tolerance
ε		strain
ε_k^m		measured strain
ε_k^t		theoretical strain
π_0		minimum level of confidence
$\Delta\sigma$	[Mpa]	stress range
$\Delta\sigma_{uA}$	[MPa/kN]	wheel type A unit stress range
$\Delta\sigma_{uB}$	[MPa/kN]	wheel type B unit stress range
$\Delta\sigma_{uC}$	[MPa/kN]	wheel type C unit stress range
$\Delta\sigma_C$	[MPa]	detail category
$\Delta\sigma_D$	[MPa]	constant amplitude fatigue limit
$\Delta\sigma_L$	[MPa]	cut-off limit
$\Delta\sigma_R$	[N/mm ²]	direct stress range
ϕ_{fat}		dynamic amplification factor
$\Delta\phi_{fat}$		additional amplification factor

List of acronyms

API	Application Programming Interfaces
ARCHES	Assessment and Rehabilitation of Central European Highway Structures
ASTM	American Society for Testing Materials
B-WIM	Bridge Weigh-in-Motion
COST	European Cooperation in Science & Technology
CSV	Comma Separated Value
DAF	Dynamic amplification factor
ERS	Electronic resistance strain
ESAL	Equivalent Single Axle Load
FAD	Free-of-Axle-Detector
FBG	Fibre Bragg Gratin
FEM	Finite Element Method
FLM	Fatigue Load Model
FTA	Finnish Transport Agency
FTIA	Finnish Transport Infrastructure Agency
GDF	Girder distribution factor
GVW	Gross Vehicle Weight
HCT	High Capacity Transport
ISWIM	International Society for Weigh-in-Motion
LAM	Liikenteen Automaattinen Mittausasema
MFI	Moving Force Identification
NAD	New Axle Detector
NOR	Nothing on road
OBW	On-Board Weighing
RC	Reinforced Concrete
ROBOT	Robot Structural Analysis software
SFS	Suomen Standardisoimisliitto
SHM	Structural Health Monitoring
WAVE	Weighing-in-motion of Axles and Vehicles for Europe
WIM	Weigh-in-Motion
cBWIM	Contactless Bridge Weigh-in-Motion

1 Introduction

Usual design service life for bridges is 100 years, which is a long time to predict the future. During this time many changes affecting the bridge performance will take place, both in physical aspects and in design principles, e.g. change in traffic load regulations (allowable weights), material deteriorating, and changes in construction and design codes. This has led to situations where the reliability of existing bridges is difficult to evaluate.

If most recent Eurocodes are applied for the capacity calculations of bridges, typically one may obtain overly conservative results that are deeming some of the existing bridges unsafe (Lilja 2018). This implies that the bridge must be repaired/strengthened or rebuilt. Both options are expensive and cause notable inconvenience for the bridge owner and users. Another notable factor when applying Eurocodes in designing is that the basis for traffic load models has been optimised for Central-European traffic (Lilja 2020a). The differences in traffic densities and the fact that the allowable weight limit for heavy vehicles is notably higher in Finland, cause more uncertainties in the design calculations and especially in fatigue analysis. For this reason, more advanced simulations and accurate data should be used to refine the results and to evaluate the specific bridge condition more accurately.

Using accurate traffic data in calculations and simulations can improve the accuracy of results significantly and in some cases even reveal hidden bridge reserves (or in special cases, as observed in the case study section 4.5.2, reveal increased damage compared to Eurocode design). By doing so, bridges can be deemed safe without expensive strengthening or rebuild measures. Weigh-in-motion (WIM) measurements are an excellent tool for bridge structural health monitoring (SHM), as it can produce quite accurate data from the actual traffic on the road. Among different WIM systems, Bridge Weigh-in-Motion (B-WIM) is one of the most suitable methods for bridge applications, as it can provide accurate information from the actual traffic on the bridge and it can be used to verify the physical behaviour of the bridge. B-WIM can recognise the number of vehicles, their gross weight, number of axles, axle spacing, weight on each axle, time, and speed of the vehicles. One of the advantages of B-WIM measurement, when compared to other WIM methods, is that there is usually no need to close the bridge during the installation of the system or during the measurements, thus minimising inconvenience caused to the bridge users.

1.1 *New traffic regulations*

Notable changes were introduced to heavy vehicle weight regulations in Finland during October 2013 (Finlex 2013). Within the regulations, multiple changes and adjustments were made to Gross Vehicle Weight (GVW) limits and maximum axle loads of heavy vehicles.

The aim of the new regulations was to decrease the transportations cost and thus increase the efficiency of the transportation industry. Increased payloads were thought to decrease the number of heavy vehicles on the road, and thus the impact to environment was predicted to be positive. Additionally, it was believed that fatal road accidents would decrease due to fewer heavy vehicles on the road. As for the negative effects, the regulations change was expected to increase the wear to the infrastructure, especially for bridges. As many existing bridges are designed with outdated codes not accounting current increased vehicle loads, an increase in fatigue damage and the need for repairs was expected to increase after the regulation change. (Rauhanen Mikko 2015)

1.1.1 Change in weight limits

In the new regulations, the most notable changes regarding bridges were an increase in the GVW limits and an increase in bogie weight limits of the heavy vehicles. These changes are presented in Table 1.

Table 1. New weight limits for heavy vehicles compared to older ones.

Truck/Axle type	Maximum GVW limit	
	Old regulations	New regulations
2-axle vehicle	18 t	20 t
3-axle vehicle	26 t	28 t
4-axle vehicle	32 t	35 t
5-axle vehicle	38 t	42 t
8-axle vehicle	60 t	68 t
9-axle vehicle	60 t	76 t
Bogie weight limit		
2-axle bogie	19 t	21 t
3-axle bogie	24 t	27 t

It is important to note that the changes presented in Table 1 are maximum limits for a certain type of truck configurations. Factors, such as axle distance, wheel type, and suspension type may have a reducing effect on the weight limits.

Special transports over the 76-ton limit are allowed with separate permission that must be applied from a governmental body. A predetermined route is assigned for these transports, taking the weight and size restrictions of infrastructure into an account. The transport is not allowed to deviate from the planned route.

Additionally, from 2013 onwards, tests with High Capacity Transport (HCT) trucks have been done in Finland. HCT trucks are longer and/or heavier truck combinations that are not classified as a special transportation. A limited amount of exemption permits has been admitted to 10 to 14-axle trucks, with weights up to 104 tons and lengths up 34 metres. These trucks are required to use predesignated routes, but otherwise are free to move without restrictions.

1.1.2 Axle load study

After the new traffic regulations were placed into an effect, a new axle load study was conducted by the Finnish Transport Agency (FTA) or now known as Finnish Transport Infrastructure Agency (FTIA). The focus of the study was to observe the average axle, bogie, and total weights of the heavy vehicles. First measurements were taken during December 2013 and second measurements were conducted during October 2014. In these measurements, dynamic axle scales and laser sensors were used respectively to determine axle weights and axle distances. Additionally, manual inspection and driver interview was conducted to determine the suspension type, wheel type, load type, and loading rate. (Toikka, Virtala 2015)

B-WIM measurements were also done as part of the study, although the results from these measurements were not included in the final report of axle load study. Multiple different bridges were selected for the B-WIM measurements during the years 2013 and 2014. Commercial B-WIM system SiWIM by Cestel d.o.o. from Slovenia was used in all the measurements. After the original two measurement periods, the study was extended, and more measurements were conducted. These measurements were taken between the years 2015 and 2017. The final report from B-WIM measurement results was released in 2018 (FTA 2018). After the report release, a few more B-WIM measurements were conducted.

The axle load study results offered an extensive overall view of the heavy vehicle traffic on the Finnish roads. The most concrete outcome from the study was the obtained Equivalent Single Axle Load (ESAL) values. However, as only two axle load measurements were conducted, both right after the regulation changes, the study did not offer an extensive view on the development of the heavy vehicle traffic. On the other hand, the results obtained with B-WIM measurements, were more continuous and thus offer a better view of the GVW change of the heavy vehicle traffic. In B-WIM Overview Report (FTA 2018), it was concluded that the transportation industry adjusted rather quickly to the new regulations. It was noticed that number of 7-axle vehicles, for which the weight limit did not change, decreased after the new regulations, and the number of 8 and 9-axle heavy vehicles increased. It was also noticed that the total GVW gradually increased after the regulation change. These trends can be seen quite well from Figure 1 and Figure 2. The data presented in these figures includes only the vehicles above the mean point of GVW in each configuration. The data shown is from Olhava site, as the measurements in there were yearly trough out the years 2013-2017.

Figure 1. Number of vehicles above mean point at Olhava (FTA 2018).

Figure 2. Average GVW at Olhava (FTA 2018).

1.2 Eurocode regulations versus old design codes

New bridges in Finland are designed according to the Eurocode and its Finnish National Annex. The load models used in Eurocode are somewhat conservative to account possible increases in the future traffic loads. Additionally, certain amount of model uncertainty is included in the load models and calculation methods. When assessing already built bridges, national guidance (FTA 2015) can be used to calculate the carrying capacity. The load models in it are more realistic and have been calibrated to better represent the typical traffic flow in Finnish road network.

During the last century, the weight limits for heavy vehicles have been increasing regularly. The upward trend in Finland can be seen in Figure 3. The new regulation set in 2013, allowed maximum of a 76-ton vehicle. Due to the change, both Eurocode National Annex and load carrying capacity calculation code were updated to accommodate the increased weight limits. The two most recent load carrying capacity changes are named as AA90 and AA13. AA90 was developed due to changes in vehicle legal weight limits during 1990, and AA13 was developed due to the most recent change in the legal weight limits set in 2013.

Figure 3. Development of heavy vehicles maximum weight limit (Toikka, Virtala 2015).

Design loads have been updated alongside the weight limit regulations changes. Eurocode based design code was adopted in Finland during 2010 and it replaced the old national codes. In 2013 the National Annexes of Eurocodes were calibrated due to the new regulations allowing 76-ton vehicles. The previous design load models can be seen from Table 2.

Table 2. Previous design load models (Lilja 2018).

Name	Year	Description
3T - 12T	before 1940s	- 2*12-ton or 2*9-ton vehicles - Evenly distributed load 400 kg/m ² and 3-12-ton vehicle
A II/RKM	1950s-1953	- 120 kN axle + 9-18 kN/m line load
A I/RKM	1953-1969	- 140 kN axle + 12-24 kN/m line load
Special vehicle 134T	1961	- 134-ton special vehicle
Ak I / Ek1	1969-1971	- AK I: 140 kN axle + 12-24 kN/m line load - Ek1: Special transportation load 4*300kN
PKM 71 / RKM 1975	1971-1991	- 3*21-ton axle + 0.3 t/m ² even load
Lk I (Lk2) / Ek1	1991-2010	- Lk1: 3*210kN axle + evenly distributed 9kN/m line load to whole lane width - Ek1: Special transportation load 4*300kN
Eurocode LM 1/ LM3 (NCCI 1 2010)	2010-2014	- LM1: 1 st lane 2*300kN axles + 9 kN/m ² ; 2 nd lane 2*200kN axles + 2.5 kN/m ² ; other lanes 2*100kN axles + 2.5 kN/m ² LM3: Special transportation load 2*1350kN
Eurocode LM 1/ LM3 (NCCI 1 2014)	2014-	- LM1: 1 st lane 2*300kN axle + 9 kN/m ² ; 2 nd lane 2*300kN axle + 6 kN/m ² ; other lanes 3 kN/m ² LM3: Special transportation load 2*1350kN

A problem related to the outdated design codes exists when carrying capacity and the condition of existing bridges is assessed. Older codes were not designed to consider the current heavy vehicles, implying that bridges designed with these codes can have inadequately carrying capacity for current traffic. This problem is mostly limited to older codes, as usually future development is somewhat considered and by default, codes should provide conservative designs. This can be observed in Figure 4 where the Lk I / Ek1 code used before the Eurocodes is still valid for vehicles assessed with AA13 carrying capacity code.

Figure 4. The ultimate limit state design loads compared to 2013 traffic regulation load capacity in ultimate limit state. AA13 is 76-ton vehicle limit and AA90 is 60-ton. (Rauhanen Mikko 2015).

Earlier it was discussed that especially fatigue analysis has inaccuracies when using Eurocodes for Finnish traffic. Fatigue damage is dependent on the cyclic loads and their amplitudes affecting the structure. In the case of bridges, this denotes that the traffic flow and the weight of the vehicles are the main factors regarding fatigue life. When the weight of the vehicle doubles the fatigue damage increases eightfold, denoting that even small inaccuracies in axle load estimations may cause large errors in fatigue analysis. As the traffic load models in the Eurocodes are optimised for Central-European traffic, the difference to the actual traffic in Finland causes multiple uncertainties in the calculations.

1.3 Existing bridges in Finland

In the beginning of 2020, there were 11 784 bridges (excluding steel pipe culverts) on public road network in Finland. Most of these bridges were built between 1955-2000. This denotes that many of these bridges are designed with old codes where the design loads are smaller than today. Figure 5 shows bridges constructed in past the 120 years.

Figure 5. Number of bridges built in different years (FTIA 2020).

Mainly bridges in Finland are in good or decent condition. This can be seen from Figure 6 which shows the current condition of bridges and the evolution of bridge condition in the past decade. Generally, most recently constructed bridges are in excellent condition, and older the bridge is, the worse its condition change. Mainly though, the number of bridges in the lowest categories is quite low. In future though, this might change as the effects of the new traffic regulations and heavier vehicles of it begin to show on the older bridges.

Figure 6. Bridge condition trend between 2011-2020. (FTIA 2020).

1.4 Lack in Bridge Weigh-in-Motion Standardisation

B-WIM is an excellent tool for vehicle weight tracking and can be also used in bridge health monitoring. Recent developments in the field have increased accuracy and possible applications of it. Especially the European Cooperation in Science & Technology (COST 323) action (Jacob et al. 2002) brought many advancements to the WIM and B-WIM measurements. Still, the use of B-WIM is mainly focused on the research field and occasionally it is applied for vehicle overweight monitoring and traffic analyses. Partly due to this, the data produced in B-WIM measurements is quite fragmented as most of the institutes or companies have their own methods for the data presentation and processing. Even though in the COST 323 action a certain standard format for the output data was suggested, the lack of coordination between institutes have led to a situation where multiple different formats are in use.

The lack of widely used standards for the output data presentation, hinders the broader use of B-WIM measurements in bridge designing field. As most of the data produced in different occasions are in different formats, an extensive amount of work is needed to be able to compare different measurements together or use them in analysis software. With a single standardised format, utilising data from different countries would be more streamlined and more extensive analyses could be done.

European Union has detailed plans to improve road safety in EU countries. One aspect of this is better enforcement of weight limits for heavy vehicles. In directive 2015/719 {13} (Council of the European Union 2015), it is stated that the member states should take more measurements by 2021 in identifying overweight vehicles either with onboard weighing systems, conventional static systems, or WIM systems. This could increase the demand for B-WIM systems which could, on the other hand, increase the amount of B-WIM data produced. Without proper standardised format for the B-WIM data and cooperation between institutes, many countries might implement their own methods and unofficial standards for the measurements. This could lead to a situation where a large amount of B-WIM data is produced, but its utilisation in other applications would be difficult. With proper standardisation, the data produced in weight limit enforcement could also be efficiently utilised in bridge engineering.

1.5 Scope and goals of the thesis

The goal of this thesis is to study B-WIM technology and determine what kind of raw data one can produce with B-WIM measurements, and how such data could be utilised most efficiently in the bridge designing. Based on the findings, a new standardised way for data presentation will be suggested. This would unify the data produced by B-WIM measurements and make it easier to utilise in analyses. The comparison of data from different countries would be easier, and it could also streamline the process of utilising B-WIM data in analysis software by eliminating the need for adjusting the data format to software-specific needs.

The first part of the thesis consists of a literature review regarding B-WIM technology. In this chapter, the basic principle of B-WIM technology and variations of it are introduced. It will also consist of a brief look into the theory of the B-WIM systems and the advantages/disadvantages of it. Lastly, the applications of the B-WIM measurements are

inspected. This chapter should provide readers a comprehensive view of the basic principle of B-WIM systems and offer a basis for the rest of the thesis.

In the second part, the already existing B-WIM data presentations are inspected and compared. Based on the findings in the literature review and from the other used B-WIM data presentations, a standardised presentation is proposed. Additionally, interviews with Finnish Transport Infrastructure Agency and Swedish company Trafikia are conducted to further improve the applicability of the proposed format.

For the third part, a case study from an orthotropic steel bridge deck is performed by using already existing B-WIM data. In the case study, bridge fatigue damage is evaluated by using the B-WIM data, and the results are then compared to values calculated according to Eurocode fatigue load model 4 (FLM 4). To calculate the fatigue from B-WIM data, a fatigue calculation software is coded by using Python programming language. The case study will also act as a proof of concept to demonstrate how utilisation of standardised B-WIM data can be beneficial in bridge designing.

2 Bridge Weigh-in-Motion

The main purpose of WIM systems is to determine the total weight of the vehicles driving past the measuring point. Most of the WIM systems can also determine axle weights, axle distances, number of axles, and speed of the vehicles. To measure these values, multiple different kinds of instruments and methods can be used. The most common ones are sensors installed directly into the pavement, which can measure the dynamic tyre force caused by the passing vehicle. From the dynamic force, the static weights of the axles can be determined and with the timing between each measuring sensors and each axle, other parameters mentioned above can also be calculated. WIM systems possess multiple different applications, from which the most common ones are legal weight limit enforcement and research purposes.

Bridge Weigh-in-Motion is one variation among different WIM methods. In B-WIM, instead of using sensors imbedded in the pavement measuring the dynamic force caused by tyre, the bridge itself acts as a measuring instrument. The vehicle driving over the bridge cause strains to the structure that are usually measured with strain gauges installed to the underside of the bridge slab or girders. In addition, so-called axle detection sensors are used to measure the speed of the vehicle, axle distances, and the number of axles. By applying these parameters and the influence line concept, the axle weights and total weight of the vehicle can be determined from the strain data.

2.1 History

The weight of vehicles is and has typically been a central point of interest for road infrastructure owners and law enforcement. Heavier vehicles usually cause higher wear for the infrastructure, and in some cases, overweight vehicles might even cause severe accidents and costly damage to infrastructure. Repairing these is expensive and cause notable inconveniences for the road users. Due to these reasons, the weighing of vehicles, especially the heavier ones, has been interest of infrastructure owners.

Most basic vehicle weighing systems are static scales. In static scales, the vehicle is driven on top of the scale where it stays stationary during the measurement. The system can be permanently installed or portable, thus offering a wide range of applications. Static measurement is the most accurate measurement method for vehicle weighing, but it is slow as every vehicle has come to a halt for the measurement. This makes it quite impractical for vehicle weight monitoring on roads as the measurements can interrupt the traffic flow and cause notable delays.

The need for faster measurement methods created interest in WIM systems. In WIM systems, the vehicle weight can be measured while the vehicle is moving, decreasing the disturbances to traffic flow. The development of the first WIM systems started around the 1960s (Richardson et al. 2014). These systems usually use devices, such as bending plates, strip sensors, load cells, and capacitance mats, mounted in the pavement to measure the vehicle weights.

The first B-WIM system was introduced by Moses (1979) during the 1970s. Moses was the first one to propose use of influence line and measured strain data to minimise the difference between predicted bridge response and measured response. This method is known as Moses'

algorithm and is still the basis for most B-WIM methods. Moses' first B-WIM systems consisted of strain gauges, operator, and axle detection. First, the operator activates the system when the vehicle is approaching the measurement point. Then sensors on the lane, such as tape switches, record the vehicle speed, axle configuration, and axle distances while the strains are measured with strain gauges installed underside of the bridge deck. The first systems were primitive compared to modern systems, and even though the early iteration managed to obtain quite accurate results, the system had quite limited applications due to the multi-vehicle problems and dynamic effects.

In the 1980s, the Axway system was developed by Peters (1984). The system is based on the same influence line concept as Moses' system. A few years after this, Peters (1986) developed a better known system called Culway. In a similar way to Axway, Culway was based on Moses' B-WIM system, but instead of bridges, it used culverts as the measurement instrument. This had the advantage of reducing inaccuracies due to dynamic effects. The surrounding soil in culvert systems has a damping effect on the vibrations, thus reducing inaccuracies. Still, the Culway system received only little interest outside of Australia.

The development of B-WIM technology was slow until the 1993 when European COST 323 (2002) action was initiated. After it, the Weighing-in-motion of Axles and Vehicles for Europe (2001) (WAVE) program was started to continue the development to B-WIM technology. During these programs, multiple advancements were achieved regarding the axle detection and influence line calculation. These advancements significantly increased the accuracy of B-WIM systems. These projects also led to a development of the SiWIM system, which is currently the only widely available commercial B-WIM measurement system. (Richardson et al. 2014)

In past years, the development of B-WIM has mostly focused on improving the accuracy and extending the range of applicability of B-WIM systems. These have been achieved by improvements in Moses' algorithm and more advanced post-processing and filtering methods. However, there are still problems in implementing these theories and advanced methods to field measurements and commercial use. (Lydon et al. 2016)

2.2 Different WIM systems

2.2.1 Pavement-based WIM

In pavement-based WIM systems, the measuring device is installed directly to the pavement. When a vehicle drives over it, the dynamic tyre force from the vehicle is measured. Depending on the measuring sensor a signal, such as voltage, strain, or resistance, is measured and sent to the computer. The computer processes the signal and calculates the desired data from it. For measuring, multiple different sensor types are available for WIM systems. The optimal sensor is chosen based on multiple different criteria set by the application of device, location, and cost. In some systems, inductive loop detectors, cameras, laser scanning or other similar instruments are utilised to detect and classify the vehicles. (Al-Qadi et al. 2016)

The most common sensors applied in WIM systems are:

- bending plate sensor,
- load cell sensor,
- piezoelectric sensor,
- piezoceramic sensor,
- piezopolymer sensor,
- piezoquartz sensor, and
- fibre-optic sensor.

The WIM systems can be divided into two classes: low-speed and high-speed WIM systems. In low-speed WIM, the vehicle speed can vary from 5 km/h to 15 km/h, while maintaining high accuracy. In the axle load study (Toikka, Virtala 2015), a dynamic scale, which is low-speed WIM, was used to measure axle weights. Low-speed WIM is optimal for weight inspections due to their high accuracy, but their measuring speed is quite slow, and they suffer from similar problems as static scales. Low-speed WIM requires vehicles to slow down and possibly to move away from the road to the measurement point, causing disturbances to the traffic. Moreover, measuring points usually require expensive staff to run the measuring process, increasing the costs. On the other hand, this allows more comprehensive inspection of the vehicle, and properties, such as suspension type, loading rate, fuel type, and wheel configuration can be determined.

High-speed WIM systems are usually installed directly to the pavement and can operate without vehicles slowing down. This reduces the traffic disturbances when compared to static scales and low-speed WIM systems but with the cost of accuracy. Moreover, high-speed WIM measuring points are usually unmanned, providing lower operating costs and enabling 24 hours a day measurement. The disadvantage of these systems is that during the installation and maintenance, the lane needs to be closed causing disturbances to the traffic. Furthermore, additional support structures might be required for the system, increasing the construction costs and time. (Richardson et al. 2014)

2.2.2 B-WIM

B-WIM algorithms can be generally divided into two different categories: static algorithms and dynamic algorithms (Yu et al. 2016). Static algorithms aim to obtain the static weights of the vehicle by smoothing out the dynamic components. Dynamic algorithms, on the other hand, try to obtain the time history of the axle forces, thus taking the dynamic movement of the vehicle into account. Dynamic algorithms are also known as moving force identification (MFI) methods.

2.2.2.1 Static algorithms

Most of the static algorithms are on some level based on Moses' (1979) theory and are usually some sort of a variation of it. In Moses' algorithm, the actual bending moments at the bridge are calculated from the measured strains and then compared to the theoretical moments obtained with axle weights and the theoretical influence line of the bridge. From Figure 7 it is visible how the moment at the mid-point can be calculated from the influence line and the axle weights. Figure 8 presents an illustration from the strain signal under the load and how each axle causes a strain peak when it is directly over the sensor location. In

the algorithm, the main goal is to calculate the unknown axle weights. As the actual bending moment and the theoretical bending moment can be set equal, the unknown axle weight can be solved the equation. As multiple axles exist in the measured vehicle, multiple different equations are required to solve all the unknowns. From every measurement timestep, one equation can be formed; thus, the number of axles in the vehicle is also the minimum number of timesteps required to solve all the unknown axle weights. However, in Moses' algorithm, many extra timesteps are included to increase accuracy. The resulting measurements for the axle weights and GVW are calculated by utilising the least-square method to minimise the error between measured moments and theoretical ones. A more in-depth view of the theory of Moses' algorithm is elaborated in section 2.3.1.1.

Figure 7. The principle of moment calculations from the theoretical influence line, where M is the moment at the mid-point (strain gauge location) for this exact truck position; A is the axle masses; and I is the influence ordinates (Žnidarič, Kalin 2020).

Figure 8. Illustration from the strain gauge data under the vehicle load.

Many factors can affect the accuracy of Moses' algorithm. The three most notable ones are the transverse position of vehicle, condition of the derived system equation and dynamic effects. In Moses' algorithm, the dynamic inaccuracies originate from the differences between the dynamic axle load and the theoretical static influence line. When a vehicle

drives over the bridge, vibrations in the vehicle and in the bridge causes oscillation in the measured strain. In Figure 8, the strain data is presented as a smooth line, but in reality, it is much rougher due to the dynamic effects and the noise in the measurement devices. In Moses' algorithm, this is filtered by using a large amount of time steps obtained by every vehicle pass and utilising the least-square method. But even after the filtration, the dynamic effects can still cause large inaccuracies if the road surface or approach span of the bridge is in poor condition. The transversal position of the vehicle might also affect the accuracy in some bridges. This problem becomes more critical for multilane roads, but even with single-lane bridges, the transversal position of the vehicle in the lane might cause errors in the results. This issue is also apparent when multiple vehicles are on the bridge at the same time, making the identification of each vehicle axle difficult. The last problem in Moses' algorithm relates to the system equation being ill-conditioned. This is usual in measurements where the pavement on the bridge is rough or the measured vehicles has closely spaced axles. This problem is related to the solution of axle weights being sensitive to the measurement noise. (Yu et al. 2016)

To improve the inaccuracies caused by the transversal position of the vehicle in Moses' algorithm, a two-dimensional influence line algorithm was proposed by Quilligan et al. (2002). Two-dimensional influence line or also known as influence surface (not to be confused with the influence area method), considers also the load effects of the transversal position of the unit load as the regular influence line only considers the longitudinal position. Otherwise, the method utilises the same error minimisation principle to obtain the axle weights as Moses' algorithm. As the influence surface can account for the transversal position of the vehicle, inaccuracies due to position of the vehicle on the lane decrease notably. The influence surface algorithm is also able to accurately measure individual axle weights while multiple vehicles are on the bridge simultaneously. (Quilligan et al. 2002)

Ojio and Yamada (2005) suggested employing reaction forces at the support for simply supported bridges to measure the vehicle weights. For reaction forces, the peak of the influence line is right at the support denoting that when a vehicle enters the bridge, a large peak in support forces can be measured. The peak can be thought to be solely caused by the axle entering the bridge thus the axle weight can be determined from the peak height. Even though this method is simple to implement and use, it is uncommon due to a few larger disadvantages. Like pavement WIMs, the reaction force algorithm is also sensitive to the dynamic effects as the measurement is taken from a single point instead of the whole bridge length. This is quite problematic with expansion joints as they can cause excess vibration just at the start of the measuring point. Another problem with the algorithm is the difficulties of reaction force measurements in practice.

The influence area method (Ojio, Yamada 2002) utilises the concept that the area of the response curve can be utilised to calculate the GVW. The area of the response curve can be calculated from the product of the influence line area and the GVW. As the influence line must stay constant, the equation can be set so that the GVW divided by the response area is constant. This constant can be calculated by utilising a calibration vehicle with a known GVW. As the response area can be obtained by numerically integrating the response curve of the vehicle, the constant can be multiplied by the area to obtain the GVW. In this respect, the Influence area method is simple to use and implement. It does not require any axle detection or complicated calculations. However, there is one significant disadvantage in the

method, in that measuring the individual axle weights is rather difficult with this method, thus restricting its use to applications where only the GVW is of interest.

2.2.2.2 Moving Force Identification

The dynamic effects on B-WIM measurements are caused by the vehicle vibrations and vibrations caused to the bridge by the moving axles. These vibrations affect the strain measurements of the B-WIM, causing dynamic inaccuracies in the GVW and axle weight calculations. In Moses' algorithm, these are filtered by utilising the vast amount of data and least-square method to smooth out the dynamic components. MFI methods, on the other hand, try to obtain the complete time history of the axle forces from the passing of the vehicle. When the whole force history of the time varying forces is obtained, the dynamic effects can be recognised and excluded when calculating static axle weights. (Yu et al. 2016)

The first MFI method was developed in the 1980s by O'Connor and Chan (1988). This method is an interpretive method applying the element model to calculate the force history. The system consisted of lumped masses, which were interconnected with massless elastic beam elements. When the displacement or moments of the system nodes are known, the axle forces can be solved from a set of linear simultaneous equations by applying the least-square method. Moreover, instead of the finite element model, the Euler-Bernoulli beam can be used to solve the moving axle forces. When employing the Euler-Bernoulli method, the measured response is firstly transferred to modal displacements and then the velocity and acceleration can be derived from it. Again, a set of linear simultaneous equations is obtained from which the time history of the axle force can be calculated by applying the least-square method. To solve these equations, a sufficient number of strain gauges are required compared to the number of axles in the vehicle. Later, the Timoshenko beam model was also applied instead of the Euler-Bernoulli beam model. (Yu et al. 2016)

In 1997, Law et al. (1997) applied the time domain method based on modal superposition to obtain the time history of axle forces. The method also applied the Euler-Bernoulli beam as the base equation of it. A few years later, Law et al. (1999) also applied the frequency-time domain method for the Euler-Bernoulli beam. Here, the Fourier transformation is used to transform the displacement into the frequency domain where the axle forces are identified. Then, the inverse Fourier transformation is applied to obtain the axle force time history in the time domain. The frequency-time domain method gathered significant amount of interest, and multiple improvements to the accuracy and utilisation of the model was suggested.

Many other methods and variations of the interpretive, time domain, and frequency-time domain methods were suggested. This included both new applications and more accurate and better conditioned algorithms. Moreover, both 2D and 3D finite element methods (FEM) were combined with other methods to improve the results. With these advancements, the MFI methods has become rather accurate when properly implemented. Still, the applications for the MFI methods has been quite limited and mostly restricted to scientific use. The main reason for this is its complicated implementation on real bridges. Most of the MFI methods are still based on simple elements, such as beams and plates, decreasing their accuracy when implemented to more complex bridge structures. These structures require more complex 3D models to yield accurate results. The complexity of the MFI algorithms also requires a vast amount of computational power, making those too complex to apply in real-time weight

identification. Thus, MFI has the potential to be an excellent tool in the future, but at the moment static methods outweigh the use of it in commercial systems due to their simplicity and ease of use. (Yu et al. 2016)

2.2.2.3 Contactless B-WIM

Contactless B-WIM (cBWIM) measures the deflections of the bridge and utilises those to calculate vehicle weights in a similar manner as in normal static B-WIM measurements. The difference is that instead of using sensors attached to the bridge structure, cameras are utilised to measure the deflections and axles. The concept system tested by Ojio et al. (2016) consisted of two time-synchronised consumer grade cameras equipped with high-speed movie mode. One camera measured bridge underside deflection with sub-millimetre accuracy, and the second camera monitored vehicles passing over the bridge deck. For deflection measurements, a tripod, spotlight, and camera with added extra telescope were used. Camera was focused on a sensor attachment bolt to obtain clear focus point for later image analysis. The camera monitoring bridge deck was used for axle detection, axle spacing, and vehicle speed calculations. The obtained video feed was processed with modern image analysis tools to obtain the vehicle parameters and deflections. After it, a modified Moses' algorithm was applied to obtain the GVW and axle weights. (Lydon et al. 2016)

The advantage in cBWIM system is its easy and cheap to set up. Installing cameras on to the underside of the bridge is simpler than installing strain sensors. This could be advantageous in situations where the underside of the bridge is restricted or difficult to work on. As with other nothing on road (NOR) WIM systems, cBWIM does not require the closure of the lanes during installation, thus decreasing the disturbance to traffic. In their research, Ojio et al. (2016) found out that the achieved accuracy of cBWIM systems was relatively low and in addition, multiple calibration runs with known weight test vehicle was required for each setup. Like with other B-WIM systems, the values for GVW were more accurate than single axle weights in closely spaced axle groups. In some cases, the difference was quite notable, but it was suspected that this might have been due to the low sampling rate of the camera system.

Currently, conventional B-WIM offers greater accuracy compared to cBWIM, but with improved instruments and measuring methods, cBWIM could become a feasible option for a short period and low-cost measurement applications. Ojio et al. (2016) also did some theoretical simulations with different bridge lengths, where they found out that an increase in bridge length could actually improve the accuracy of the system and thus offer a great alternative for longer bridges. Still, further research from cBWIM is required to increase its potential among other B-WIM systems.

2.2.3 Other similar systems

Culway is B-WIM based system that uses culverts as measurement instruments instead of bridges. Peters (1986) developed the Culway system in Australia, where it became quite common WIM system. Outside of Australia the interest in the Culway was rather small and thus, most applications of it stayed in Australia. Currently, more advanced version Culway II, developed by APRB, is available and used in Australia. The Culway system was a further development from Peters earlier AXWAY system (1984) which, on other hand, was based on Moses B-WIM system. Culway was developed to be unmanned and low-cost WIM

system that could be easily installed and used. It consists of two axle sensors on the pavement detecting the vehicle and measuring its properties; multiple strain gauges with amplifier attached to the culvert for the weight calculation; and a central computer to store and process the data. The advantage of Culway was its low sensitivity to dynamic effects and vibrations due to soil damping. Also, the simpler structure of culvert often signifies smoother pavement at the measurement point and just before it, furthermore, lowering the dynamic effects. The accuracy of it also made it a suitable WIM choice, but interest in the Culway in its early days and the development of other B-WIM systems, that could be utilised on wider range, have reduced its usage outside of Australia. (Richardson et al. 2014)

LAM (Liikenteen Automaattinen Mittausasema in Finnish) -points are automated stations gathering information from traffic passing over them. LAM-points utilise induction loops embedded into the pavement to measure the electromagnetic induction caused by metallic mass of the passing vehicle. Two induction loops are installed in succession at each lane and connected to centralised computer that processes the data and sends it forward. LAM-points can measure time, driving direction, driving lane, vehicle speed, vehicle length, and the vehicle type. Currently there are approximately 500 active LAM-points located in Finland. Data from these points is openly shared by Finnish Transport Infrastructure Agency.

Induction as a measurement method is not accurate enough to determine the actual weights of the vehicles, but it can still rather accurately determine the type of the vehicles. The vehicle types are categorised into seven different groups, excluding motorcycles that can be only be detected by the newest LAM-systems (type DSL-6). So, the LAM data itself cannot be used for GVW measurements, axle weight analyses, or in simulations where accurate or historic vehicle/axle weight data is needed, but it can work as an excellent tool when utilised alongside the B-WIM data. For example, the B-WIM measurements conducted in Finland mostly lasted from one to two weeks. Extrapolating such data to a longer period might cause inaccuracies due to seasonal changes in traffic. By using vehicle type data obtained from LAM-points one can extrapolate the B-WIM measurements more accurately into a longer period. Iso-Junno (2017) applied this method in his master thesis by calculating average daily traffic from one-year period utilising LAM data and then deriving factor for B-WIM data to account seasonal changes in traffic. He then conducted fatigue analysis for the Jännevirta-bridge by applying the extrapolated B-WIM data. In the thesis, he found out that this method yielded quite accurate results for the traffic even though the B-WIM measurement period was only one week.

On-board weighing (OBW) systems are directly installed to the measured vehicle instead of infrastructure. This offers accurate and up to date information from the GVW and axle weights. Sensors in this system are installed to the measured axle. The different types of sensors used in OBW systems are load cell, air pressure, and strain gauge sensors. The applications can be either static, where the weight is measured when the vehicle is stationary, or dynamic, where the weight is measured during the movement of the vehicle. Most of the OBW systems are static as the measurements are more reliable and accurate, but interest in dynamic applications is growing as it allows dynamic load balancing of the axles, increasing efficiency and safety of the heavy vehicles. Currently, most of the OBW systems in use are for commercial use of the companies to increase truck fleet management possibilities and to ensure vehicles staying under the maximum load limits. Currently, the governmental applications for OBW systems are non-existent, but propositions for using it as a way to remotely check the vehicle weights have been suggested. This could additionally increase

the interest of companies in investing in OBW systems as vehicles with the system could bypass weighing points thus saving time. (ISWIM, 2020)

2.3 B-WIM operation principles

Typical B-WIM system has three main components; strain gauges, axle detectors, and a central computer. Figure 9 shows components of commercial SiWIM system, where in addition to the main three components, some additional ones can be seen. The strain gauges are usually installed side by side to the central span of the bridge. These measure the global strains in the bridge structure and are the main instruments in vehicle weight calculations. For axle detection, there are multiple different options that are discussed more in section 2.3.1.3, but mainly they are either sensors installed on the road surface or sensors installed underside of the bridge as in Figure 9. Axle detection is used to detect the number of axles, their spacing, and speed of the vehicle. Lastly, the central computer stores and processes the data obtained from the sensors and if needed sends it forward to a server or other devices. The central computer can take its power from an electric network or in remote locations from a battery. Other additional equipment is solar panels to charge the batteries, camera to follow the traffic, communication antenna to send the data during the measurements, and extra sensors, such as temperature or acceleration sensors, to provide additional data.

Figure 9. SiWIM system components: (1) axle detection (FAD type), (2) spider, (3) strain gauges, (4) central computer, (5) battery, (6) solar panels, (7) solar panel installation, (8) antenna, (9) camera, (10) graphical user interface (Yu et al. 2016).

2.3.1 Basic theory

2.3.1.1 Moses' algorithm

Many B-WIM applications are based on Moses' algorithm which is applied in varying forms on modern B-WIM systems. The algorithm utilises the fact that bending moments in the

bridge can be calculated from the measured strains and also with influence line ordinates and the actual axle weights. For a section of the bridge, the bending moment can be determined with equation

$$M = EW_i \varepsilon_i , \quad (1)$$

where E is the elastic modulus of the material, W_i is the section modulus of the i th girder/section, and ε_i is the measured strain in the i th girder/section. Total bending moment in the bridge can be obtained by summing the bending moments obtained from all the strain gauges that are in same longitudinal location.

$$M_k^m = \sum_{i=1}^G EW_i \varepsilon_i , \quad (2)$$

where G is the number of strain gauges, M_k^m is the total measured bending moment on timestep k , and EW is girder/section dependent constants that can be calculated from bridge dimensions and used materials. In practice, it is common to determine these values with calibration runs, where a vehicle with known axle weight is measured from which the bridge properties are reversely calculated.

In the second part of the Moses' algorithm, theoretical bending moments are calculated by using influence line and axle weights. Influence line shows force effect caused by unit load to certain point, usually midpoint, of the structure. When certain point of the influence line is multiplied with the load located at that point, the force effect in measuring point is obtained. In Figure 10, the influence lines for bending moments of simply supported and fixed bridge can be seen. In the first applications of Moses' algorithm, the theoretical influence line was used.

Figure 10. Influence line for simply supported bridge (left) and fixed bridge (right).

The total theoretical bending moment can be calculated on timestep k by using superposition principle and multiplying all the loads at the bridge by corresponding influence ordinates.

$$M_k^t = \sum_{i=1}^N A_i I_{(k-c_i)} , \quad (3)$$

$$C_i = \frac{D_i f}{v} \quad (4)$$

In equation (3) N is the total number of axles, A_i is the weight of the i th axle, and $I_{(k-c_i)}$ is the influence ordinate at i th axle position. In equation (4), D_i is the distance between first and i th axle, f is the scanning frequency, and v is the velocity of the vehicle. The velocity of the vehicle is usually assumed constant.

In theory, the measured bending moment M_k^m and theoretical bending moment M_k^t should be the same, and thus equation combining both can be formed. When axle weights are unknowns, theoretically N amount of timesteps would be a sufficient number of equations to solve all the unknown axle weights. In practice, this does not work as the measured response is not static but includes dynamic components that increase the inaccuracies. In Moses' algorithm, the dynamic effects are evened out by using a large number of time steps what are produced during the passing of each vehicle. The values for axle weights can be calculated with least square method and for this, an error function E , with total number of T time steps, is formed (Moses 1979):

$$E = \sum_{k=1}^T [M_k^t - M_k^m]^2, \quad (5)$$

The best values for axle weights can be obtained by minimising the error function. This can be done by taking partial derivate from the said function with respect to each of the axle weights and setting the sum to zero. The axle weights A_i can be solved with equation:

$$\frac{\partial E}{\partial A_i} = 2 * \sum_{k=1}^T (M_k^t - M_k^m) * \frac{\partial (M_k^t - M_k^m)}{\partial A_i} = 0. \quad (6)$$

The GVW can be obtained from the sum of the axle weights:

$$GVW = \sum_{i=1}^N A_i, \quad (7)$$

2.3.1.2 Strain measurements

Strain gauges are one of the most crucial part in most of the B-WIM measuring systems. They are the basis for the axle weight calculations thus incorrect strain gauge selection could lead to inaccurate results or even failure of the whole measurement test. The gauges need to be able to measure strains accurately without large background noises and be able to operate in challenging outdoor environments. Other requirements, such as long durability, might be needed depending on the application and intended use.

Common types of strain gauges used in B-WIM measurements are (Lydon et al. 2016, Yu et al. 2016):

- electronic resistance strain (ERS) gauges,
- vibrating wire strain gauges, and
- fibre optic sensors.

From these three, ERS gauges, also known as foil strain gauges, are the most common in B-WIM systems. The gauges contain strips of metal foil, usually in Wheatstone configuration to amplify the signal, that when strained change their electrical resistance. From it the equivalent strain change can be calculated. Sensor can be directly installed to structure or strain transducer can be used to allow reusability of the sensors. ERS gauges possess a decent accuracy and are quite cheap, making them suitable choice for short-term measurements and experiments. The disadvantage of ERS gauges is their poor durability and susceptibility to environmental factors and electromagnetic interferences. Due to these reasons, a long-term B-WIM application using ERS gauges is not optimal choice. It is also good to note that ERS sensors requires power to operate, which requires extensive amount of wiring and reliable power source.

Vibrating wire strain gauges use changes in wire vibrations to measure the strains. When strain changes, the tension of a wire inside the gauge changes which also changes the wire resonance frequency. Measuring the change of the resonance frequency allows to calculate the change in strain. Vibrating wire strain gauge can be easily installed to the surface or inside of the structure and it offers a good accuracy, but it has a low scanning rate. This makes it suboptimal in recording the dynamic effects in the bridge and to accurately measure fast moving vehicles.

Last commonly used sensors are fibre optic sensors such as fibre bragg grating (FBG). These sensors use change in lights wavelength to measure strains in the structure. FBG sensors possess multiple advantages compared to two previous ones. FBG sensors are small and can utilise a multiplex what makes them optimal choice on large multi-sensor measuring setups. FBG sensors possess high accuracy and if needed, their scanning rate can achieve up to 2 kHz. The sensors are immune to electromagnetic interferences increasing the accuracy. FBG's are also durable suggesting that they are optimal solution for long-term monitoring. FBG sensors are well established in SHM applications but in B-WIM systems their usage has still been low. Lydon et al. (2016) reviewed suitability of FBG sensors in B-WIM systems, and found out that their accuracy and other properties would make it ideal choice as a strain gauge of B-WIM systems. The only major disadvantage of FBG sensors is their higher price compared to other strain gauges.

2.3.1.3 Axle detection

The main purposes of axle detection are to measure the number of axles, their spacing, and speed of the vehicles. Most of the B-WIM algorithms requires these measurements to be able to calculate axle weights accurately, thus proper and accurate axle detection is important. Inappropriately implemented or otherwise faulty axle detection might have a great impact on the accuracy of the B-WIM measurements. Axle detection systems usually consists of two consecutive sensors whose distances from each other are known. When timing between each passing axle is known, values above can be determined. In some applications, third diagonal sensor is installed between two typical sensors to measure the transversal location of the vehicle (Quilligan et al. 2002). In overall, axle detection can be divided into two broad categories; pavement systems and free-of-axle-detector (FAD) / nothing on road (NOR) systems. Pavement systems are installed on the bridge deck and FAD systems are usually installed beneath the deck. In this thesis, the strain gauge-based axle detection systems are referred to as FAD systems and in overall axle detection systems that are not installed on the pavement are referred to as NOR systems.

The first B-WIM applications utilised axle detectors installed into the pavement. In Moses (1979) B-WIM system, a simple tape switches installed to the lane were used to obtain the axle count, spacing, and speed of the vehicles. In equation (4), it can be seen how these values affect the calculations. Pneumatic tubes and low-grade piezo-electric sensors were also used in the earliest B-WIM systems. These methods are simple and offer good accuracy but their exposure to the traffic and environmental effects makes them prone to deterioration. Additionally, the installation requires lanes to be shut down, and the visible sensors on the road might change behaviour of drivers what is not desirable. These disadvantages have decreased pavement axle detection use in the modern systems.

During the WAVE project, FAD was first time proposed to be used in B-WIM measurements. This was done as one of the test bridges had a thin pavement layer. It caused concerns that installing the axle detectors on road surface may cause damage to the waterproofing layer. Thus, installing axle detectors on road was forbidden and FAD systems was proposed to be installed under the bridge deck (O'Brien et al. 2001). In FAD, usually two or more consecutive strain gauges are installed below the bridge deck. When vehicle drives over the bridge deck, a peak in the strain data can be observed on each axle passing (Figure 11). With two consecutive strain sensors, the time between these peaks can be obtained and when distance between sensors is known the velocity can be calculated.

Figure 11. FAD strain measurements of two-axle vehicle on (a) orthotropic deck and (b) slab deck (O'Brien et al. 2001).

In FAD, the correct strain sensors placement is important to obtain accurate and reliable axle detection. Single axles are usually easy to identify, but in axle groups with closely spaced axles, the identification becomes more challenging. The placement of the sensor is dependent on the bridge type. Usually, the gauges are installed where the single axle or wheel induced strain peaks are the sharpest, as it helps the identification of closely spaced axles. For example, in Figure 11 (a), the sensor in the orthotropic deck is installed on the thinnest part of the deck and under the most probable wheel path to obtain as sharp as possible strain

peak. When deck thickness increases, the strain peaks become more difficult to identify. This effect is apparent when the influence line of different thickness decks is observed (Figure 12).

Figure 12. Influence line on different deck thicknesses (O'Brien et al. 2001).

On thicker deck the strain peak from the axle/wheel widens and if multiple axles are closely spaced, the strain peaks can blend together making the axle identifying practically impossible (Figure 13). The effects of different bridge types can also be seen in the figure.

Figure 13. Response for double-axe bogie in two different types of bridges. Bridge deck thickness is expressed as percentage of span length. (O'Brien et al. 2001).

If FAD is used in orthotropic bridge, it is usually installed to the underside of the deck slab similar as in Figure 11. Sometimes this may cause problems in the axle identification. If the wheel of the vehicle is transversally located right on top of the loadbearing girder, the strain peaks may not be clear enough in the slab. Figure 14 shows well how this effect fuses strain peaks together in the closely spaced axles and makes the axle identification practically impossible. It is good to note that, the vehicle in Figure 14 (a) was partly loaded (22 t) and the vehicle in (b) was overloaded (41 t).

Figure 14. (a) Clear strain peaks at axles when wheel is on the slab (b) fused peaks when wheel is located directly over the girder. (Lydon et al. 2017).

Few different methods have been suggested as a solution to this problem. O'Brien et al. (2012) suggested using a shear strain sensors (Figure 15 (a)) for the axle detection. In their paper, they conducted a numerical investigation for the use of shear strain sensors in the axle detection. They found out that the peaks in shear strains were sharp and large enough for modern sensors to be able to use them in the axle detection. Kalhori et al. (2017) found out in their field test that shear strain sensors installed close to the support were able to detect even closely spaced axles reliably. Another method suggested by Lydon et al. (2017) utilised compressive strain measurements in the girder for the axle detection. The strain sensors were installed to the girder of the bridge so that it could measure the compressive strains (Figure 15 (b)) caused by the vehicle. In the research, they found out that this sensor placement, when installed close to the support, offered a reliable way to detect the axles and offered an increased accuracy in the axle detection compared to the typical FAD/NOR systems. It was suggested that combining the typical FAD axle detection and New Axle Detector system could offer a great solution for axle detection that could also take the transversal location of the vehicle into consideration.

Figure 15. (a) Suggested location at the interface of the web and flange for shear strain sensor (O'Brien et al. 2012). (b) Suggested location for the New Axle Detector (NAD) sensor (Lydon et al. 2017).

After the initial implementation of FAD, interest in axle detection by only using the weighing sensors was increasing as it would provide a cost-effective and setup wise simple way to

detect the axles. The problem with using weighing strains in the axle detection is that in many cases the peaks in weighing data are not sharp enough for the axle detection. Chatterjee et al. (2006) used a wavelet-analysis in their experiments to better identify closely spaced axles. In their tests, reverse biorthogonal wavelet method (rbio2.4) was applied, and it was able to reveal 5 clear peaks corresponding to the measured axles of the vehicle (Figure 16, scale 16). They came into conclusion that employing wavelet method can increase the accuracy of the axle detection and help identify closely spaced axles even when those cannot be directly identified from the strain data. Initially, the wavelet method was used with typical FAD setup to improve the accuracy of it, but later, applications for axle detection straight from the weighing sensors were developed. (Yu et al. 2016)

Figure 16. Wavelet coefficient of the original strain signal using rbio2.4 (Chatterjee et al. 2006).

In addition, few other methods were suggested for the axle detection. Lechner et al. (2010) suggested using the crack opening in concrete as an axle detection method. They noticed that crack openings in the concrete slabs were rather sensitive to axle loads, and it was suggested that it could be used as an axle detection method. This method did not see much of a success as applications of it are limited only to bridges with large enough crack openings. The most recent and interesting development in axle detection is video-based detection methods. As described in section 2.2.2.3, a camera installed to the deck of the bridge takes a video from the wheels of the passing vehicle, and by using advanced image analysis tools, the axles are detected from the video. The method is especially interesting as the development in the image-processing field has been great in the recent year thus offering interesting applications in the axle detection and in B-WIM field overall.

2.3.1.4 Influence line and girder distribution factor

In Moses' algorithm, the influence line is used to calculate the theoretical bending moments caused by the unknown axle weights (equation (3)). If the assumed influence line is not corresponding to the actual influence line of the bridge, it can cause large inaccuracies in the results. Thus, finding a correct influence line for the bridge has been a point of interest in B-WIM research quite a long time.

In original Moses' algorithm, the influence line for bending moment is used to obtain the bending moments. This denotes that elastic modulus and section modulus are needed for the calculations. If a FEM model of the bridge is built or drawings of the bridge are acquired, calculations of these parameters are not too complicated. For practical B-WIM applications, the influence line is usually determined with calibration vehicles, as it can be too time-consuming and expensive to calculate the bridge parameter values. In these cases, the influence line for strains can be used instead of the typical bending moment influence lines, thus the following equation can be obtained:

$$E = \sum_{k=1}^T [\varepsilon_k^t - \varepsilon_k^m]^2, \quad (8)$$

where ε_k^m is the total measured strain on timestep k and ε_k^t is

$$\varepsilon_k^t = \frac{1}{EW_i} \sum_{i=1}^N A_i I_{(k-C_i)} \quad (9)$$

$$\rightarrow \varepsilon_k^t = \sum_{i=1}^N A_i I_{(k-C_i)}^{strain}, \quad (10)$$

where $I_{(k-C_i)}^{strain}$ is the influence line for strains.

The first B-WIM applications used theoretical influence lines for bending moment in the calculations of the axle weights. Those were sufficient enough to calculate the GVW's but lacked the accuracy to calculate the axle weights in most cases. In most of the real-life bridges, the influence line of the bridge is something between fixed span and simply supported span. This is because the actual support conditions in the bridge are usually more complicated and something between these two. To improve this, a spring type of support was suggested in the 1990s, to imitate the condition between fixed and simply supported (Figure 17). Additionally, the peaks of the influence line were smoothed slightly as the actual peaks in the influence line are not sharp but rather round. This is due to the deck thickness dividing the load into a slightly larger area, which was demonstrated in Figure 12. These parameters were determined via calibrations by using known weight test vehicles. The problem with the method is that it still uses a simple influence line model as the basis, thus limiting the applications to only simple bridges. (O'Brien et al. 2006)

Figure 17. Theoretical, measured and partly fixed influence line for case analysis (Mandić Ivanković et al. 2019).

Later, point-by-point graphical method (in some literature referred to as DuWIM) was tested to derive more accurate influence line. In this method, the theoretical influence line was manually adjusted so that the influence response would closely resemble the response of the test vehicle. In Figure 18, a comparison between the theoretical influence line and adjusted influence line is seen. Point-by-point method can offer an accurate way to derive the influence line, but the method is time-consuming as it is done manually, and the end result is highly dependent on the skill of the operator.

Figure 18. The actual response and theoretical influence response (a) when using theoretical influence line and (b) when using point-by-point derived influence line. (McNulty, O'Brien 2003).

To improve this, O'Brien et al. (2006) suggested a computational method to derive the influence line. The influence line is calculated by utilising Moses' algorithm and a known weight test vehicle. The error function is minimised similar manner as in Moses' algorithm, but in this case as the axle weights are known, the function is minimised regarding the influence line. In the field tests, O'Brien et al. obtained rather accurate results for the influence line, particularly for the two- and three-axle calibration vehicles. It was later pointed out that this method was prone to perturbations due to the noise in specific signals. To improve this maximum likelihood estimation principle can be applied (Yu et al. 2016).

All the previous methods for determining the influence line have assumed that the bridge behaves like a single 1D beam. This denotes that the transversal load distribution characteristics of the bridge are not considered. Zhao et al. (2014) proposed an improved

version from numerical method suggested by O'Brien et al. (2006), where every girder had its own influence line calculated and the load distribution factor for every girder was accounted. The method was proven accurate in the field test conducted for concrete slab-girder bridge. In the field test, they found out that the accuracy of this method was similar to the bending plate WIM measurements that were also conducted at the bridge site. Multi-vehicle presence was not considered in the study.

The girder distribution factor (GDF) denotes how the loads located on the lanes are distributed to the different girders. Mostly, the loads are distributed to the girders under the lane and the further away the girder is from the lane, smaller the girder distribution is. For example, Zhao et al. (2014) found out in their research that in their slab-girder case bridge almost 80% of the loads were undertaken by the two girders right under the lane, 20 % was undertaken by the third girder next to the lane, and only under 5% was undertaken by the fourth and farthest girder. For the opposite lane, this girder distribution was other way around. Largest distribution was on the girder 3 and 4 located under the lane and lowest was in the girder 1. GDF can be used as a tool to refine the B-WIM calibration and accuracy as described earlier. It can also offer a greater insight from the structural behaviour of the bridge and be used as a measuring point in structural health monitoring. Applications of GDF are introduced more in section 2.5.1.1.

2.3.1.5 Data post processing

2.3.1.5.1 Dynamic effects

The vehicle axle loading to the bridge is not static but dynamic, as multiple different dynamic forces are acting on the vehicle and axles. This cause dynamic movement in the vehicle's body and tyres. Two main dynamic movements in the vehicle regarding B-WIM measurements are body bounce of the vehicle, where the whole vehicle body moves, and axle hop, what is bouncing of the axles (Figure 19). For body bounce, the usual frequency is around 1-4 Hz as for the axle hop it is typically 10-15 Hz. Other axis movements might also be present but are usually neglectable compared to the main two.

For B-WIM systems, the dynamic effects are usually smaller than in pavement WIM systems as the measurement period on the bridge is longer, thus averaging out the dynamic effects. However larger bumps and defects on the road might still cause considerable dynamic movement in the vehicle and thus increase the inaccuracies in the measurements.

The dynamic components in the axle loads are noticeable in the measured strains. In Figure 20, the combination of the static axle weights and varying dynamic components can be seen in the measured strain (red line). As described previously, in Moses' algorithm, the dynamic components are averaged out by utilising large amount of measured data in the averaging process. The algorithm calculates the static axle weights, and from these and the bridge influence line, a theoretical static response can be calculated (blue line). The dynamic component can be seen in the measured strain by comparing it to the calculated static strain. The black columns in the figure presents the axle locations and green lines are influence lines at axle position.

Figure 19. Dynamic movements of the typical vehicle, 1. body bounce, 2. body pitch, 3. axle hop, 4. Bogie(tandem/tridem) pitch.

Figure 20. Strain response of 8m integral concrete bridge under a 43.8t vehicle. (Kalin et al. 2015).

A dynamic amplification factor (DAF) is used to present the dynamic effects in the loads. The DAF is defined as a ratio between maximum total load effect (dynamic + static) and maximum static load effect. In B-WIM, this is simply the ratio between the maximum measured strain (Figure 20 red line) and maximum static response (blue line) (Kalin et al. 2015). DAF values are important part of designing and offer a simple way to evaluate the dynamic load effects to the bridge. As DAF values can vary notably depending on the vehicle and bridge characteristics, the DAF values determined in Eurocodes are in most cases conservative.

There are a few different methods to calculate the DAFs in B-WIM measurements. The first method utilises the calculated axle weights to determine the theoretical static response with the use of influence lines. When the theoretical strain is obtained, the maximums for the measured strain and theoretical static strain can be obtained, and the ratio between them can be calculated. The disadvantage of this method is its dependability on the correct axle weight and axle detection calculations. This is particularly problematic in cases where the DAF is high as those are usually the cases where miscalculations are present in the axle weights or other parameters. This usually has the effect of either overestimating or underestimating the DAF and making them unrealistically large or small. Another method to estimate the theoretical static response is the filtering of the signal. As the frequencies of the dynamic components in the strain signal are usually higher than the static ones, a low-pass filter can be set to filter the high frequency dynamical vibrations out from the signal. First, the measured strain signal is transformed to the frequency domain by using the Fourier transform and then a low-pass filter is applied. After that, the signal can be converted back to the time domain, and theoretical static strain can be obtained. By comparing it to the measured strain, the value for DAF can be calculated. The filtration method can be also applied to increase the accuracy of B-WIM algorithm by minimising the dynamic effects in the data. The problem with filtration is that in reality, the difference in frequencies of the static signal and dynamical signal is not always clear, especially for longer, low frequency bridges. Determining the cut-off point for the low-pass filter requires a highly skilled operator as otherwise the filtered signal might become smeared or some dynamic components might still be present in the signal. A good example of this is from McNulty's and O'Brien's (2003) research where the low-pass filter was used to minimise the dynamic effects. The filter was set too low thus the peaks from the closely spaced axles were also filtered out (Figure 21). This caused some of the closely spaced axles to become unidentifiable. (Kalin et al. 2015)

Kalin et al. (2015) reviewed a new method in their research that utilises a combination of these two previously mentioned methods to calculate DAF. In this new method, axle weights are first calculated. Then based on those, parameters for a piecewise linear low-pass filter are determined. These parameters are calculated separately for every vehicle. This denotes that for some of the vehicles the parameters are incorrect due to the miscalculated axle weights. To counter this the mean value for the parameters, from multiple different vehicle passes, is chosen as the final parameters. When final parameters are chosen, the dataset is reprocessed using the final filter parameters, and the DAF values for each vehicle are calculated. This method is also adapted to the commercial SiWIM program.

Figure 21. Comparison between unfiltered and filtered strain signal with 4-7 Hz transition band (McNulty, O'Brien 2003).

In ARCHES (Assessment and Rehabilitation of Central European Highway Structures) project (2009) and multiple different papers released after it (Žnidarič, Lavrič 2010, Kalin et al. 2015, Mandić Ivanković et al. 2019), it is demonstrated with theoretical means and with field tests that the DAF decreases when the loading on the bridge increases (Figure 22). Also, the standard deviation decreased with the increasing axle weights. This is true for both single vehicle and multiple vehicle presences. This implies that in extreme load cases (multiple presences) the DAF is usually closer to 1. In many codes, especially the older ones, DAF's are constant values, thus overestimating the dynamic effects for heavy vehicles and underestimating them for lighter ones.

Figure 22. DAF for Ivanje selo viaduct. (González et al. 2009).

2.3.1.5.2 Environmental effects

In the WAVE project (O'Brien et al. 2001), it was concluded that environmental factors have only a small influence to the accuracy of B-WIM measurements, especially if appropriate strain measurements, that can compensate for temperature changes, are used. Different seasons have also a small effect to the accuracy if the temperature variation during the measurement period remain moderate. There is still some possibility for notable error due to the temperature effects on strain gauges. It should be noted that some of the strain gauges are more susceptible for environmental effects as discussed in section 2.3.1.2.

For longer period measurements, where the environmental changes are larger, better and repetitive calibration might be needed. By repeating the calibration runs in two notably different temperatures, coefficient value for temperature changes can be determined. In some cases, extreme temperature changes, e.g. summer versus winter, may notably affect the bridge physical behaviour and cause large inaccuracies. McNulty and O'Brien (2003) found out in their research that their measurement results from the summer and winter varied significantly from each other. They notice differences in the bridge response and influence lines during the wintertime and suspected that frozen supports might have been the reason for the change.

As the certainty of the measurement accuracy decreases when measurement duration increases, an environmental repeatability class for certain measurement can be assigned according to COST 323 action. When calibrations are conducted and accuracy classes for the WIM system are determined, the set environmental repeatability class affects the accuracy classes. The environmental repeatability is divided into three different classes according to COST 323 action (Jacob et al. 2002, section 11.1.4):

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

2.3.2 Advantages and limitations

The main advantage of WIM systems is the capability to measure the vehicle axle weights, axle dimensions, and other vehicle parameters while the vehicle moving. This enables weight limit enforcing and traffic information gathering without disturbing traffic. When compared to the traditional WIM systems, B-WIM has few clear advantages.

The main advantages are:

- Modern B-WIM systems do not require any installations to the pavement.
- B-WIM systems are portable and easily transferable.
- B-WIM measurements can offer additional information from the measured structure.
- As the measurement period for the vehicle is from the whole length of the bridge, the dynamic loads are less significant.

As common B-WIM systems do not require any installations or modifications to the pavement, it can be installed without damaging the existing pavement layer and without needing to close the lanes. This minimises the traffic disturbances and increases the safety of the personnel installing the system. An additional advantage of this is that B-WIM system is less visible making it more difficult for overweight vehicles to avoid the measuring point. The portability of the B-WIM system also helps as changing the measurement point from time to time makes it more arduous to map out the weighing points. This is also better in traffic analysis sense as it allows wider a range of measuring points offering more diverse traffic data. The portability and easy installation make it a great tool for short period measurements. In case of structural information, it can be used to analyse the performance of the bridge and it can reveal critical information from the bridge condition or other aspects. For traditional WIM systems, the dynamic loads can be a large problem. If the road surface before the measurement point is in poor condition, it can cause excessive dynamic movement in the vehicle, which in the measurements is seen as larger dynamic loads. In WIM, the measurement period for the vehicle is usually short increasing the dynamic effects. For B-WIM the measurement period for the vehicle is the whole length of the bridge which decreases the effects of the dynamic effects.

In overall the constrains for WIM systems is their somewhat low accuracy when compared to static measurements. This restricts their use in applications where error margins are low, such as enforcing the weight limits. When comparing B-WIM systems to other WIM systems the main disadvantages and limitations are:

- The accuracy of the B-WIM system is highly dependent on the complexity of the bridge structure, thus restricting its usability and accuracy.
- Difficulties to implement the most recent development in practice.

The main disadvantage of B-WIM systems is the variability from bridge types, requiring a certain degree calibration for each specific bridge. The more complex the bridge structure is, the more difficult it is to accurately calibrate it. Additionally, problems with the multivehicle presence increase the difficulties to apply B-WIM systems to longer bridges and roads with multiple lanes. Although many researches have been conducted to overcome these problems and better results have been obtained, implementing these advancements to commercial systems has been difficult. Most of these solutions work only for certain situations and bridge types, requiring an extensive amount of work to implement. This makes them more expensive and less desirable in commercial applications.

2.4 WIM measurement standards

COST 323 is widely approved and adopted standard for WIM use, especially in Europe. In addition to COST 323, another widely used specification for WIM is the American Society for Testing Materials (ASTM) standard ASTM E1318 – 09 (2017), which is mainly adopted in the US. In general, the ASTM standard is more focused on the pavement WIM systems, and therefore the B-WIM systems are not much described in the standard. It is still commonly applied to the B-WIM measurements as well, especially in case of accuracy classes.

The main focus in this section is on COST 323 action and its recommendation and procedures, as it is the main guide used in Europe and it also takes B-WIM measurements into consideration better. The US standard ASTM E1318 – 09, is additionally taken into comparison for the parts it is regularly used in B-WIM field.

2.4.1 Bridge site requirement

In the B-WIM measurements, the correct selection of bridge site is crucial part of the measurement procedures. In COST 323 (Jacob et al. 2002) action, it is stated that the accuracy of the measurements is highly dependent on the site selection. The major two aspects that affect the accuracy in B-WIM measurements are the pavement condition and bridge type. If pavement is in poor condition, it might cause excessive dynamic vibrations in the vehicle decreasing the measurement accuracy. The bridge type itself might also decrease the accuracy of the results, and in overall the common B-WIM systems cannot be applied to all the bridge types.

In COST 323 (Jacob et al. 2002, section 5.2) action, the pavement condition is divided into three different classes:

- **I** Excellent
- **II** Good
- **III** Acceptable

The definition of these classes is further described in the COST 323 action. The basic bridge selection criteria recommendations can be seen in Table 3.

Table 3. Bridge selection criteria recommendations (Jacob et al. 2002).

Criteria	Optimal	Acceptable
Bridge type	Steel girder, prestressed concrete girders, RC girders, culverts, steel orthotropic decks ⁽¹⁾	Concrete slab
Span length ⁽²⁾⁽³⁾ (m)	5 – 15	8 – 35
Traffic density	free traffic – no congestion (traffic jam)	
Pavement condition	Class I or II	Class III
Skew (°)	≤ 10	≤ 25 or ≤ 45 ⁽⁴⁾

⁽¹⁾ Expected to be optimal according to WAVE program (O'Brien et al. 2001)

⁽²⁾ Applies for length of the bridge part which influences the instrumentation

⁽³⁾ Expect culverts

⁽⁴⁾ After inspection of the calibration data

2.4.2 Calibrations

Calibrations are an important part of the WIM setup procedures and are used to assure proper accuracy for the results. The extent of calibration is dependent on the application of the system and the wishes of the customer. With more extensive calibrations, the accuracy level of the system can be increased, but the cost and time to conduct the calibrations will also increase. There are multiple different calibration methods for different WIM systems, but for B-WIM systems the most usual method is to use pre-weighed trucks.

Four different test condition determined according to COST 323 (Jacob et al. 2002, section 7.2.3):

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

These conditions affect the total accuracy class of the measurements which are discussed in section 2.4.3. In addition to this, environmental repeatability is also considered when determining accuracy class. The environmental repeatability classes are shown in section 2.3.1.5.2. For WIM systems the (R1) condition is recommended. In addition, to these conditions, a minimum of 10 successful test runs per lane are required. It is also recommended that the calibration vehicle has at least one tandem or tridem axle. For fully loaded calibration runs, the expected mean GVW should be used, especially in (r1) case or other cases where only one vehicle is used in calibration. After the tests, a calibration value is obtained which is used to multiply the raw data to obtain the final axle weights. The calibration results should not show any nonlinearity regarding the loading or speed of the vehicle. If nonlinearities are observed, influence line, measured vehicle speed, or other parameters should be checked.

The calibration runs can be repeated in the end of the measurement period to ensure that the system has been working properly and to calculate the drift during this period. The drift can be used to normalise any anomalies that may have occurred during the measurement period. It can be also used to determine the temperature effects on bridges assuming that the temperature difference between initial and end calibrations is large enough.

Similarly to the COST 323, the calibration processes and recommendation are described in ASTM E1318 – 09 (2017) as well. These are used to define the accuracy class for the system and to verify the proper operation of the system. In the scope of this thesis, these are not be discussed in further detail.

2.4.3 Accuracy classes

In COST 323 action, one of the main priorities was to develop a means to evaluate the accuracy of the WIM measurements. As the accuracy of different systems and sites may vary notably and as the applications might have different accuracy requirements, seven different accuracy classes were defined (Table 4). These classes are A(5), B+(7), B(10), C(15), D+(20), D(25), and E, where the class E can be divided into a subclasses (Table 5) if needed. The accuracy classification is based on statistical comparison between measured WIM weights and corresponding true weights. Usually the true weights are obtained by static weight measurements. The numbers in the brackets represent the tolerance (confidence interval width δ (%)) for the gross weight of the vehicle. In addition to the GVW, the classes are specified also by tolerance of the axle group, single axle, and axle within a group. The overall accuracy class of the WIM system is determined by the least accurate item. In addition, if the same data is used in calibration and in accuracy evaluation, the confidence interval is multiplied by factor of 0.8, when determining the accuracy class of the system. (Richardson et al. 2014)

Table 4. Tolerances for accuracy classes determined in COST 323 action (2002).

Type of measurement	Domain of use	Accuracy Classes: Confidence interval width δ (%)						
		A(5)	B+(7)	B(10)	C(15)	D+(20)	D(25)	E
1. Gross weight	GVW > 3-tons	5	7	10	15	20	25	>25
Axle load:	Axle load > 1-ton							
2. group of axles		7	10	13	18	23	28	>28
3. single axle		8	11	15	20	25	30	>30
4. axle of a group		10	14	20	25	30	35	>35
Speed	> 30 km/h	2	3	4	6	8	10	>10
Inter-axle distance		2	3	4	6	8	10	>10
Total flow		1	1	1	3	4	5	>5

Table 5. Tolerances for class E determined in COST 323 action (2002).

Type of measurement	Accuracy Classes: Confidence interval width δ (%)					
	E(30)	E(35)	E(40)	E(45)	E(50)	etc.
1. Gross weight	30	35	40	45	50	...
Axle load:						
2. group of axles	33	39	44	49	55	...
3. single axle	36	42	48	54	60	...
4. axle of a group	41	47	53	59	65	...

To calculate the accuracy class, the minimum level of confidence π_0 is determined. It can be determined based on the sample size, test condition, and environmental repeatability. The corresponding minimum level of confidence can be determined according to COST 323 section 11.3 (Jacob et al. 2002). The minimum allowed tolerance $\delta_{\min}$ (the width of the confidence interval for individual WIM measurement) can be calculated with the minimum level of confidence π_0 and from the normal distribution of calibration data. The accuracy class is then determined based on the next accuracy class from $\delta_{\min}$.

In the ASTM E1318 – 09 (2017) standard, four different accuracy classes are specified for WIM measurements as can be seen from Table 6. In Weigh-in-Motion Pocket Guide (2018), those are described as following:

- **Type I and Type II:** Suitable for traffic data collection purposes, with Type I systems having slightly more stringent performance requirements. Vehicle speed range to meet functional performance requirements is 10 to 80 mph.
- **Type III:** Suitable for screening vehicles suspected of weight limit or load limit violations and have stricter functional performance requirements than Type I and Type II systems. Vehicle speed range to meet functional performance requirements is 10 to 80 mph.
- **Type IV:** Not approved for use in the United States but intended for use at weight enforcement stations. Vehicle speed range to meet functional performance requirements is 2 to 10 mph.

Table 6. Accuracy classes according to ASTM E1318-09 (2017).

Function	Accuracy Classes (tolerance for 95% compliance):				
	Type I	Type II	Type III	Type IV	
				<i>Value $\geq$ lb (kg)</i>	<i>$\pm$lb (kg)</i>
Wheel load	$\pm 25\%$		$\pm 20\%$	5000 (2300)	250 (100)
Axle load	$\pm 20\%$	$\pm 30\%$	$\pm 15\%$	12000 (5400)	500 (200)
Axle-group load	$\pm 25\%$	$\pm 20\%$	$\pm 10\%$	25000 (11300)	1200 (500)
GVW	$\pm 10\%$	$\pm 15\%$	$\pm 6\%$	60000 (27200)	2500 (1100)
Speed			± 1 mi/h (± 2 km/h)		
Axle-spacing			± 0.5 ft (± 150 mm)		

To give the readers idea of typical B-WIM accuracies, a set of measurements are presented in Table 7. Various algorithms and methods were used in these measurements.

Table 7. Different B-WIM measurement and their accuracy classes. Underlined accuracies denote the overall accuracy of the measurement.

Paper	Method	Author	Bridge type	Length	Other/ note	Single axle	Axle group	GVW
1.	1D-influence line	(O'Brien et al. 1999)	RC box girder	11.5 m	American system	<u>E(50)</u>	<u>E(50)</u>	D+(20)
	“	“	“	“	Irish system	<u>E(50)</u>	<u>E(50)</u>	D+(20)
2.	1D Influence line	(WAVE WP1.2, 2001)	Orthotropic steel deck	92.5 m /64.8 m		<u>D+(20)</u>	<u>D+(20)</u>	<u>D+(20)</u>
	2D Influence line	“	“	“	Optimisation algorithm based on 2-D bridge model	<u>C(15)</u>	<u>C(15)</u>	<u>C(15)</u>
3.	1D-influence line	(WAVE WP1.2, 2001)	RC integral two span	≈10 m	Skew 7°	<u>C(15)</u>	B+(7)	B+(7)
	“	“	“	“	Skew 26°	<u>D+(20)</u>	B+(7)	B(10)
4. (Lulea bridge)	SiWIM	(WAVE WP1.2, 2001)	RC integral two span	14.6 m	Summer 1997	<u>C(15)</u>	B(10)	<u>C(15)</u>
	SiWIM (adjusted temperature)	“	“	“	Winter 1998	<u>C(15)</u>	<u>C(15)</u>	<u>C(15)</u>
	“	“	“	“	Summer 1998 Adjusted results	<u>B(10)</u>	<u>B(10)</u>	B+(7)
5. (Lulea bridge)	Point by point method ⁽¹⁾	(McNulty, O'Brien 2003)	RC integral two span	14.6 m	Summer 1997	<u>C(15)</u>	B(10)	B(10)
	“	“	“	“	Winter 1998	C(15)	<u>D+(20)</u>	C(15)
	“	“	“	“	Summer 1998	<u>B(10)</u>	<u>B(10)</u>	<u>B(10)</u>
6.	1D model	(Quilligan et al. 2002)	RC integral single span	10 m	Matrix method derived IF	<u>B(10)</u>	B+(7)	<u>B(10)</u>
	2D Influence surface	“	“	“		<u>B+(7)</u>	A(5)	<u>B+(7)</u>
	2D Influence surface (multiple presences)	“	“	“		<u>B(10)</u>	A(5)	<u>B(10)</u>
7.	SiWIM	(Tiehallinto, 2008)	RC integral single span	7.2 m	First Finnish B-WIM test	<u>C(15)</u>	B(10)	<u>C(15)</u>

⁽¹⁾ Also referred to as DuWIM in some literature.

2.5 Applications of B-WIM

2.5.1 Application in bridge engineering

2.5.1.1 Bridge properties validation and Structural health monitoring

Structural health monitoring is a process of identifying changes in the structure behaviour, by utilising different monitoring systems installed to the structure. If changes are noticed, data-based evaluation can be done to identify the location of damage and the extent of it. Typically, automated damage detection algorithms are used in damage identification. SHM systems offer a variety of interesting aspects to bridge maintenance. Traditionally, the damage detection of bridges has conducted with a series of inspections by engineers. The extent of these inspections depends on the age and other details of the bridge. These inspections are usually rather expensive and may not reveal hidden damage of the structure. Thus, a vast amount of research has been conducted on SHM application on bridge engineering. The problem with the SHM applications is that the systems are relatively expensive, especially for long period measurements, and in most cases, the damage detection from measured changes is rather difficult.

In addition to traffic details, B-WIM systems can provide other useful information regarding the bridge properties. Information, such as influence line, girder distribution factor, and dynamic amplification factors, can be obtained as a part of the measurements. These properties can be used in SHM as damage indicators.

Influence line is dependent on the sectional properties and support conditions of the bridge. Notable changes in the measured influence line could be an indication of damaged. Especially damage on the supports could be spotted from the influence line as it is quite sensitive to the changes in support conditions. In McNulty's and O'Brien's (2003) research, they suspected that difference between summer and winter influence lines might have been due to frozen supports. GDF indicates the transverse load distribution to the bridge girders. Every girder has a lane-specific value indicating the proportion of the total load taken by the individual girder. GDF can vary somewhat from vehicle to vehicle as it is dependent on the transversal location of the vehicle on the lane, but if notable changes are spotted in the mean GDF value, it might be a sign from degradation in one or more of the girders. In theory, even internal damage can be detected as the stiffness of the damaged girder decreases. This also decreases the GDF for that girder as the stiffer healthy girders are carrying larger amount of the loads. The DAF is more vehicle related than bridge related. As discussed earlier, multiple different factors may affect DAF, some of which are vehicle specific. This denotes that a variation between similar weight vehicles might be quite large making it difficult to make any conclusions without a sufficiently comprehensive database. Thus, evaluation of bridge condition using DAF may be challenging. If an increasing trend in DAF values is observed during the long period measurements, it could be a sign of the degradation of the pavement layer at the bridge or close to it. Also, a faulty expansion joint could potentially cause a large enough jump in the vehicle to affect the DAF. (Mandić Ivanković et al. 2019)

2.5.1.1 Probabilistic load assessment of existing bridges

Eurocode load models, with default values, can be used in the assessment of existing bridges, but the results are often deeming the older bridges unsafe due to many conservative

assumptions and reserves for future. For these reasons, a national load assessment code has been developed to estimate the load carrying capacity of older bridges (FTA 2015). The assessment code is based on previous national guidance and Eurocodes, and it can better portray possible loads on the bridge. However, it can still be conservative for low-traffic roads.

WIM or B-WIM systems can be used to analyse local traffic what, on the other hand, can be utilised in the assessment of existing bridges. Skokandić et al. (2016) conducted a probabilistic analysis for a reinforced concrete slab bridge built in 1969 and located in Croatia. The method they used is suitable for short and medium span bridges, where the maximum load effect occurs when two vehicles are passing each other in the point of maximum load effect (the midpoint for single span bridges). The bridge needs to be short enough as the estimation of the effects of consecutive vehicles is difficult to analyse. The case bridge was first evaluated with Eurocode based loads and deemed unsafe with linear and nonlinear analysis. After that, they evaluated the bridge with B-WIM data from the bridge site and by employing a simplified approach to model the maximum traffic effect, which was developed by Žnidarič et al. (2012). In this approach, the bending moments for every vehicle on each lane are combined to histograms (Figure 23). Based on those, a distribution curve was approximated by applying a moving average method. For this method, the measurement period has to be long enough, or other methods has to be applied to reliably forecast the extremely heavy single vehicles.

Figure 23. Histogram and approximated distribution curve for both lanes (Skokandić et al. 2017).

If assumed that the traffic in the lanes is independent from each other and two vehicles are present, one in each lane, the histograms can be convoluted to probability mass function that represents probabilistic load effects during multi-vehicle presence (Figure 24).

Figure 24. Probability mass functions for multivehicle presence event. (Skokandić et al. 2017).

The convolution curve for a single event can also be presented as a cumulative convolution curve. To obtain the effects for longer periods of time, the number of multi-vehicle presences is required. This can be obtained straight from the B-WIM data or by utilising a headway histogram. When the number is known, extreme values theory can be used to calculate the convolution curves for longer periods of time (Figure 25).

Figure 25. Convolution curves for maximum bending moment (Skokandić et al. 2017).

Skokandić et al. (2016) used upper 95 % quantile for 53 year period in their case analysis as the 53 years was the rest of the expected service life of the bridge. The bending moment was multiplied with DAF, which in their case was conservative code-based value, and then multiplied the value with GDF calculated as slab distribution factor. With a non-linear analysis, they obtained the load factor (design load divided with obtained maximum load) of 0.889 what was still too low, but on other hand, much better than the ones obtained in previous steps. In the next step of the analysis, probabilistic values for the bridge properties and materials were used, and reliability index β was calculated for the bridge (Table 8). In this step, the bending moment obtained from B-WIM data was used as a stochastic variable with statistical parameters.

Table 8. Obtained and target reliability index values (Skokandić et al. 2016).

T	1 day	2 months	2 years	5 years	53 years
$\beta_{\text{calculated}}$	4,25	3,87	3,53	3,31	2,90
β_{target}	-	-	2,88	3,14	3,62

As seen from the table, the reliability index was still too low for 53-year service life, but the bridge should be capable of bearing the traffic for another 5 years. The authors note that with DAF measurements and better material property knowledge (lower-bound properties were assumed), the sufficient results for 53-year service life could maybe have been achieved.

2.5.1.2 Fatigue analysis

As the load caused by traffic is cyclic, the fatigue life is an important design aspect in bridges. The load magnitude and number of load cycles are the main variables in the fatigue calculations. Eurocodes offer a simple calculation method for the fatigue load, but it has some limitations. The fatigue load models are optimised for central European truck traffic, causing some inaccuracies when applied in Finland. In overall, the approximation of the fatigue loads can be challenging as the variance between roads may be quite large even inside the country. The average weight of heavy vehicles and the number of heavy vehicles are more or less road section specific. WIM and LAM data can be useful tools in estimating the traffic and can offer much better insight from the actual traffic on the road. Data from B-WIM and other WIM systems can be also utilised in a more direct way to calculate the fatigue loads.

In Eurocode, the fatigue resistance for structural steel is defined with S-N-curve. The curve describes the number of cycles the material can withstand constant amplitude stress. In Eurocode SFS-EN 1993-1-9 (2005), the S-N-curves for direct stress and shear stress are determined and categorised according to different detail categories. Figure 26 shows the detail categories for direct stress. As traffic loads are not constant, the fatigue stresses also vary. To calculate the cumulative fatigue damage for non-constant amplitude stress, a Miner's rule is often used:

$$D_L = \sum \frac{n_i}{N_i}, \quad (11)$$

where D_L is the damage accumulation, n_i is number of cycles with the stress range $\Delta\sigma_i$, and N_i is the endurance for $\Delta\sigma_i$.

Figure 26. S-N curve for different details according to Eurocode SFS-EN 1993-1-9 (2005).

Figure 27. The reservoir method and evaluation of corresponding endurance.

Often, the stresses are not induced to the structure by one cycle at the time but rather are a combination of varying stress peaks. To determine the range between these stress peaks, the reservoir method or rainflow counting method can be applied (Figure 27). The reservoir method can be imagined by thinking the stress history as a water tank that is emptied from the lowest point. The height between the lowest point and surface is the range for one stress cycle. The ranges are calculated one at the time from largest to smallest.

B-WIM data can be utilised in a direct or stochastic way. In the direct process, the measured and calculated vehicle data is combined with the influence line, and theoretical stress history for the detail is calculated. The total number and ranges for stress cycles can be then obtained by utilising the reservoir or rainflow method. With S-N-curve and Miner's rule, the damage accumulation for the measurement period can be calculated. This method is quite straight forward but is dependent on the measurement period and thus might not be able to present long period trends, such as seasonal changes or increase in traffic volume. In the stochastic method, the measured vehicles are categorised and relative frequency for a different type of vehicles and their weights is determined. This data can be then fixed and extrapolated by using other available data. The vehicles are randomly assigned according to calculated vehicle frequencies and the stress ranges are calculated similarly as in the direct method. Then the damage accumulation can be calculated by utilising Miner's rule. Iso-Junno (2017) used the stochastic method in his thesis and utilised B-WIM data accompanied by LAM data to determine the vehicle database.

2.5.1.3 Design code calibration

Design codes should provide easy to use, but still accurate enough, method of calculation. The past design loads for bridges were, at least in early days, dominated by bridge self-weight, thus little attention was paid on accurate traffic load models. With advanced computational modelling more slender and lighter bridges started to emerge. In the same time, truck weights have been increasing, thus the traffic loads have become more important part of the design process and thus more accurate traffic models were required. Modern Eurocode for traffic loads in bridges (SFS-EN 1991-2, 2004) use semi-probabilistic approach utilising more specific and measurement-based loads. During the development of the code, a vast amount of WIM data from different locations was used to derive probabilistic distribution for the traffic values. E.g. extreme load for 1000-year return period was determined in Eurocode with help of WIM data. (ISWIM n.d.)

2.5.1.4 Design of nonstandard structures

Eurocode offers comprehensive design principles for standard bridge structures. However when the bridge length is over 200 metres or the structure is special otherwise, more accurate and detailed designs are required according to the NCCI 1 (FTA 2017). This is both a safety and economic issue. B-WIM data can be utilised in this process by creating a more accurate site-specific traffic and loading models for the non-standard bridge. This increases the accuracy of the models and it also ensures that excessive conservatism is not used in the design, offering a more economical and optimal solution. (ISWIM n.d.)

2.5.1.5 Determining defects criticality in new bridges

From time to time, defects are detected in brand-new bridges. These might occur because designing errors, defective materials, or mistakes done during the construction. Around 2016 it was noticed that there were some larger faults in the concrete used in few individual bridges built in Finland (Salomaa 2016). The concrete used, contained too much air due to wrongly used additives and thus was weaker than designed. This caused halts in some construction sites and one already cast concrete bridge was demolished. Demolishing other brand-new bridges would be an extremely expensive solution. Thus, more exact calculations

were suggested as those might offer a better understanding from the actual load bearing capacity of the bridge and reveal the bridge to be safe even with the weaker concrete.

One aspect of these calculations is the real traffic and load effects of it on the bridge. Utilising the data extracted from B-WIM measurements could help immensely on determining if the bridge is actually safe for traffic. By utilising the previously described fatigue and probabilistic assessment methods, the estimation of the remaining lifetime of the bridge could be possible. These calculations could save the bridge from demolition and thus the owner of the structure could avoid large economical losses.

2.5.1.6 Estimation of truck platooning effects

In platooning two or more vehicles are linked together via data connection forming a convoy. The trailing vehicles in the convoy are driving closely behind the leader vehicle and mimicking its driving actions. These vehicles share driving-related information with one another allowing fast automated reactions to the behaviour of the leading vehicle. This allows much closer driving distances as the trailing vehicles can automatically react to sudden actions.

European Automobile Manufacturers' Association (2017) says in their infographic that the advantage of platooning is that it reduces the air resistance of the trailing vehicles thus reducing their fuel consumption and the resulting CO₂ emissions. As the vehicles can communicate together, the trailing vehicles can react automatically to the actions of leader vehicle (e.g. braking) decreasing the reaction time and improving road safety. Platooning also reduces traffic jams as the spacing between the vehicles is smaller and their movement is more uniform. Platooning is expected to be useful for heavy traffic as the advantages mentioned above are in quite a large role in the transportation industry.

On the other hand, this can create problems in pavement and bridge engineering. As in platooning the vehicles are driving closely, the probability for multiple vehicles being on the bridge simultaneously increases, which increases the loading to the bridge. These kinds of effects might not be properly considered in the design codes and only a limited amount of published work has been released from the subject (Sayed et al. 2020). If proper research effort is not conducted before large-scale utilisation of platooning, the effects to the infrastructure can be difficult to predict and in the worst-case scenario, repairs to it might become expensive. Utilising B-WIM data in future research about the subject is definitely a viable option. With help of B-WIM, better profile for heavy traffic can be created and by using that profile, estimation of platooning convoys composition at the road section could be created. Taking B-WIM data from platooning convoys could also offer a better understanding of the load effects of platooning and create more accurate methods for bridge assessment. One possible application for future could be real-time tracking of the platooning convoys and calculation of their loading characteristics. The system could warn the platoon if the convoy is too large for certain road section and either break it or offer a better route option. With advanced integrated systems, it could be also possible to calculate the wear caused by the platooning convoy and automatically fix the distances between the vehicles on cases where the wear exceeds some predetermined value.

2.5.2 Other applications

Traditional applications for vehicle weighing systems have been in law and rule enforcement side. It has been applied on tolls subjected based on the weight of the vehicle or law enforcement following and fining overweight vehicles. B-WIM systems are also used in this field but usually, they work more as a pre-selective method rather than the main weighing method. This is due to strict accuracy requirements for the weighing system when used for law enforcement. In COST 323 program (2002), the recommended accuracy for direct weight enforcement was set as class A(5) or a with special agreement with legal authorities class B+(7). For some cases, it can be possible to obtain such accurate results, but this requires an optimal bridge and thorough calibrations. The advantage of B-WIM measuring system compared to pavement WIM ones is that it is practically invisible to the drivers thus making it more difficult to evade. B-WIM systems are also portable making them easier to implement to different locations.

As B-WIM systems can offer an extensive amount of vehicle information, their applications in traffic planning and management are broad. The data can be utilised in planning and designing of future road networks, transportation-related research and infrastructure maintenance planning. When vehicle distribution on the road is known, roads can be optimised and unwanted traffic, e.g. heavy traffic in the residential area, can be guided to take safer and better suiting routes. With in-depth traffic knowledge, it is also possible to develop guidelines and policies that increase road safety, creates a more durable infrastructure and reduce vehicle pollution. Most of the B-WIM systems can also produce live information making it possible to use the systems in real-time traffic management. This can be especially helpful in larger cities where congestions are a frequent problem.

One part of developing more durable infrastructure is optimising the performance of the pavement. Heavier vehicles have a much larger effect to pavement wear and failure than lighter ones. This wear is often described with ESAL value. For example, a 40-ton 5-axle semi-trailer can have ESAL value of 1.77, as for normal 1.3-ton car it can be 0.0003. This implies that wear caused by the semi-trailer is 50 000 times higher than one caused by the normal car. If the pavement is not designed for proper traffic, the damage can accumulate rather quickly, and the service life of the pavement remains short. Repairing the pavement increases maintenance costs and cause delays to road users. In worst case, the pavement damage might cause damage to vehicles or cause accidents. On the other hand, if the pavement is designed for too heavy traffic, the other properties of it might not be optimal for the road section. This again can reduce the service life of the pavement and increase costs.

3 B-WIM data standardisation

In the previous chapter multiple different applications for B-WIM were discussed, most of which would be good tools to supplement bridge designing and for performance assessment of older bridges. Still, most of the B-WIM data utilisation is focused on one-off research projects, traffic pattern studies and vehicle weight enforcements. Outside of these, the B-WIM data is not fully utilised and only a few mentions were found on actual non-research projects or studies utilising the data. Partly the reason for this is the availability of the data. B-WIM measurements are rather expensive and unlike many other traffic-related data, only a few permanent measuring points are existing. This restricts the amount of data available and the willingness of data owners of sharing it.

Another factor restricting the proper B-WIM data utilisation in designing is the lack of standardised data format. Currently, there is no widely used standardised format to present the data obtained from B-WIM measurements. This makes the available data more laborious to utilise in a larger scale and complicates the analysis process. Moreover, it discourages software developers and companies on developing B-WIM data utilising software as the data processing without standardised B-WIM database is not efficient. If the input data requires an extensive amount of modifying and work before it can be used in the analysis software, the benefits of using automated calculation processes are lost.

After the new traffic regulations changes in 2013, multiple B-WIM measurements were carried out by Finnish Transport Infrastructure Agency (see section 1.1). Thus, an extensive amount of B-WIM data was obtained. However, its utilisation outside of the original intended traffic analysis has been sparse if one-off research projects and thesis works are excluded. One reason for this is the lack of standardised format and consequential lack of software using the data. Lilja and Tirkkonen (2020b) mentions that if proper standardised data format would be created, it would enable larger utilisation of B-WIM data in bridge designing in future.

During the development of the new standardised format for the B-WIM data, both FTIA and Trafikia AB were interviewed and consulted (Silvester et al. 2020). Trafikia AB is a Swedish company and has conducted multiple B-WIM measurements in Finland and Sweden. They are working in cooperation with SiWIM producer Cestel. Trafikia has a broad experience from B-WIM measurements and were conducting the measurements for the Finnish B-WIM measurement program between 2013 and 2019. Both parties were consulted regarding the proposed standardised format.

In the new standardised format, the data is proposed to be presented in two or more separate files. This is to make the data as specific as possible without making it too complex for software and users to read. The first file is “Metadata” file which contains the basic information from the measurements, calibrations, bridge site, and so on (see section 3.3). The second file is the “Vehicle data” file which contains the actual measurements from the vehicles (see section 3.2). Additional files can be also added if needed. The main focus of this thesis was on the vehicle data file as it is the main file containing the vehicle data and is also the file used in analysis software.

3.1 Current formats in use

Currently used formats can be divided roughly into three different categories, which are Cestel's SiWIM based formats, standardised COST 323 format and other formats used in research. From these, the Cestel SiWIM format is the most common as it is the only widely spread consumer-available B-WIM system. During the COST 323 action, a standardised way to present the WIM and B-WIM data was created but this format is not commonly used. During the research, the author did not find any mention from its usage in any applications or researches. The last category consists of research projects testing new methods and postprocessing solutions. In these, the data is usually presented in various formats best suiting to the goals of the research. From Figure 28 and Table 9 the COST 323 and Cestel's SiWIM formats can be seen respectively.

System: "Name or manufacturer"					Location: "test site"					Lane N°: kk					RECORDED DATA									
Period of the test: "from date1 to date2"					Number of test vehicles: nnnn																			
Test conditions: (l to lll) and (r1 to R2)																								
Load and weights may be expressed either in kg, 100 kg, tons or kN; the unit must be specified in the headings																								
N°	Date/ time	T (°C)	V (km/h)	Type	In motion loads/weights Wd (kg)										Static loads/weights Ws (in kg)									
					GW	A1	A2	A3	A4	A5	A6	...	GA1	GA2	GW	A1	A2	A3	A4	A5	A6	...	GA1	GA2
1	5/4/98																							
2	8:10:25	9,3	85	5	38000	6400	10600	7000	7000	7000			21000		39000	6500	10800	7300	7200	7200			21700	
3	8:11:23	9,5	89	5	39600	6200	13500	6900	6300	6700			19900		40200	6600	12100	7300	7000	7200			21500	
4	8:12:28	9,7	89	5	39400	5900	10300	9400	7300	6500			23200		38500	5900	9600	8700	7900	6400			23000	
5	8:13:06	9,9	88	5	40900	7100	10100	8200	8100	7400			23700		40500	6700	10100	7900	7900	7900			23700	
6	8:13:30	10,1	87	5	40000	8100	11700	7100	7000	6100			20200		39800	7500	11800	6900	6600	7000			20500	
7	8:13:56	10,1	90	5	30700	6700	12500	2600	4200	3700			11500		28200	6700	9900	3900	4000	3700			11600	
8	8:14:54	10,1	89	5	41300	6400	9800	8300	8600	8200			25100		42800	6100	10600	8700	8800	8600			26100	
9	8:16:09	10,1	79	6	36600	6500	12400	9000	8700						35700	6400	11100	9200	9000					
10	8:16:12	10,1	85	5	40500	6500	9200	8500	8100	8200			24800		39500	6500	9400	8100	8200	7300			23600	
11	8:16:32	10,1	88	5	42200	8200	13800	6900	6500	6800			20200		42000	7800	13400	7000	6900	6900			20800	
12	8:17:38	10,1	81	5	48300	8000	13000	8900	9200	9200			27300		48600	8100	13700	8900	8900	9000			26800	
13	8:18:28	10,2	88	5	33500	6100	5600	7300	7400	7100			21800		32600	6000	5200	7000	7200	7200			21400	
14	8:19:03	10,3	89	5	48700	7800	14200	9100	8500	9100			26700		46800	7200	14500	8400	8400	8300			25100	
15	8:19:50	10,4	86	5	37400	6400	8600	7600	7500	7300			22400		38600	6200	8300	8100	8400	7600			24100	
16	8:20:49	10,5	80	6	44900	6700	7200	8300	6400	7400	8900		16300		43900	6500	7500	8000	7100	7000	7800		14800	
17	8:21:03	12	88	5	39000	6200	10100	7500	7900	7300			22700		38400	6000	9700	7400	8000	7300			22700	
18	8:21:20	12	92	5	20200	5400	5300	3500	2900	3100			9500		20600	5200	5400	3400	3300	3300			10000	
19	8:22:29	12,3	86	5	37000	6100	7900	8400	7200	7400			23000		35000	6000	7400	7800	6800	7000			21600	
20	8:23:27	12,3	95	2	6800	2700	4100								6900	2900	4000							
21	8:23:33	12,4	88	5	43300	6900	11400	8800	8200	8000			25000		45400	6700	12100	8900	8900	8800			26600	
22	8:23:37	12,8	85	5	41500	6400	8800	7800	8200	10300			26300		40500	6200	9000	7300	8000	10000			25300	
23	8:25:13	13,4	89	6	42800	8400	12200	6700	7500	8000			18900		42900	7800	12300	6900	8000	7900			19200	
24	8:25:25	13,4	87	5	31300	6500	8800	5500	5000	5500			16000		29900	6300	8200	5200	5100	5100			15400	

Type: the classification is that recommended by this specification; otherwise the vehicle categories should be given apart
- axle loads are placed in columns A1 to A6, according to the axle rank; GA1 (and GA2 if needed) contains the group(s) of axle loads
- the type may be replaced by the number of axles, or this number may be added in an additional column
- for more than 6 axles, add columns after A6; for more than 2 axle groups, add columns after GA2

STATISTICS

Cont'n

N°	Relative errors (%)										Type of axle (1=SA, 0=AoG)								Statistics of the relative errors (%)			
	GW	A1	A2	A3	A4	A5	A6	...	GA1	GA2	A1	A2	A3	A4	A5	A6	...	number	GW	SA	AoG	GA
1	-2,56	-1,54	-1,85	-4,11	-2,78	-2,78			-3,23		1	1	0	0	0			23	52	60	21	
2	-1,49	-6,06	11,57	-5,48	-10,00	-6,94			-7,44		1	1	0	0	0			mean	0,97	1,52	0,17	0,06
3	2,34	0,00	7,29	8,05	-7,59	1,56			0,87		1	1	0	0	0			st. dev	3,22	6,31	5,88	4,77
4	0,99	5,97	0,00	3,80	2,53	-6,33			0,00		1	1	0	0	0							
5	0,50	8,00	-0,85	2,90	6,06	-12,86			-1,46		1	1	0	0	0							
6	8,87	0,00	26,26	-7,69	5,00	0,00			-0,86		1	1	0	0	0							
7	-3,50	4,92	-7,55	-4,60	-2,27	-4,65			-3,83		1	1	0	0	0							
8	2,62	1,56	11,71	-2,17	-3,33						1	1	1	1								
9	2,63	0,00	-2,13	4,94	-1,22	12,33			5,08		1	1	0	0	0							
10	0,48	5,13	2,99	-1,43	-5,80	-1,45			-2,88		1	1	0	0	0							
11	-0,62	-1,23	-5,11	0,00	3,37	2,22			1,87		1	1	0	0	0							
12	2,76	1,67	7,69	4,29	2,78	-1,39			1,87		1	1	0	0	0							
13	4,06	8,33	-2,07	8,33	1,19	9,64			6,37		1	1	0	0	0							
14	-3,11	3,23	3,81	-6,17	-10,71	-3,95			-7,05		1	1	0	0	0							
15	2,28	3,08	-4,00	3,75	-9,86	5,71	14,10		10,14		1	0	0	1	0	0	0					
16	1,56	3,33	4,12	1,35	-1,25	0,00			0,00		1	1	0	0	0							
17	-1,94	3,85	-1,85	2,94	-12,12	-6,06			-5,00		1	1	1	1	1	1						
18	5,71	1,67	6,78	7,69	5,88	5,71			6,48		1	1	0	0	0							
19	-1,45	-6,90	2,50								1	1										
20	-4,63	2,99	-5,79	-1,12	-7,87	-9,09			-6,02		1	1	0	0	0	0						
21	2,47	3,23	-2,22	6,85	2,50	3,00			3,95		1	1	0	0	0	0						
22	-0,23	7,69	-0,81	-2,90	-6,25	1,27			-1,58		1	0	0	1	1	1						
23	4,68	3,17	7,32	5,77	-1,96	7,84			3,90		1	1	0	0	0	0						

GW= gross weight
SA= single axle
AoG= axle of a group
GA= group of axles

- the relative errors are calculated cell by cell from the previous part of the sheet using the formula: $e = (Wd - Ws) / Ws$
- the type of axle can be delivered by the WIM system, or derived from the axle spacing (AoG if the spacing is less than 2.2 m)
- the statistics of the relative errors are calculated using formula, which combine the relative errors and the type of axle cells

Figure 28. Standardised presentation for B-WIM data according to COST 323 action (Jacob et al. 2002).

The standard format in the figure is presented in the COST 323 action appendix IV (Jacob et al. 2002). The appendix describes the standard format for the data and computer tools for accuracy assessment. This format is not in common use as it has become outdated and is not suitable for current needs of the B-WIM users and applications. For example, the format does not describe the axle spacings which is an important aspect in most B-WIM applications. Moreover, after the COST 323 the WAVE project (O'Brien et al. 2001) was initiated to continue the B-WIM development in Europe and during it, the SiWIM system was developed in close cooperation. The emergence of SiWIM has also initiated the move from COST 323 standard to other formats.

Table 9. Data presented in SiWIM system's NSW file (FTA 2018).

Field	Data	Comments and units
1	Timestamp	Format is YYYY-DD-MM-HH-MM-SS-mmm
2	Offset	[s], measured from start of corresponding .nacq file
3	Site ID	
4	Session ID	
5	Warning flags	See table 4 for meaning of these
6	Lane	
7	v	[m/s], speed
8	N	Number of axles
9	Subclass ID	
10	Axle groups	E.g., 113 for a semitrailer
11	W_{GV}	[kN], gross vehicle weight
12	W_1	[kN], axle 1 load
:	:	:
11 + N	W_N	[kN], axle N load
12 + N	$\sum_{i=1}^{N-1}$	[m], total axle distance
13 + N	A_1	[m], distance between axles 1 and 2
:	:	:
11 + 2N	A_{N-1}	[m], distance between axles N-1 and N
12 + 2N	T	[°C], temperature used for compensation
13 + 2N	Impact Factor	
14 + 2N	$1000 \cdot Q$	Quality estimate

In SiWIM the vehicle data is stored in its own text-based NSW file format described in Table 9. This format is used to move the vehicle data between different SiWIM standalone modules and can be also used to export the data into Excel. Additionally, strain measurements and signals from axle detection are saved as binary acquisition NACQ files. The SiWIM has the separate modules for in site calculations, front end applications, post-processing and web-based applications. (FTA 2018)

The format used in SiWIM has most of the crucial information regarding common B-WIM applications in it but lacks in few aspects discussed more in the next section. The major disadvantage in the SiWIM data presentation is its own NSW file format. This is problematic as importing and parsing such file format to other software may cause compatibility issues. The format is also susceptible for changes due to Cestel deeming modifications to the format or to the SiWIM necessary. This could be problematic for analysis software using B-WIM data, especially if the developers are not in close cooperation with Cestel. Changes to the format could make the newer measurements unreadable without

changes to the analysis software. Additionally, if other B-WIM systems are developed to commercial use in the future, the developer of said systems might not consider using another's company way of presenting the data appealing. This could divide the data presentation into multiple different formats and thus decrease the usability of all B-WIM data. The same problem is apparent as well if WIM system's data is also wanted to be implemented to the analyses.

For these reasons, a new standardised B-WIM data format is proposed. The new format should be comprehensive enough that the data could be utilised in as many as possible applications. It should also be easily accessible by different programming language and spreadsheet programs so that it can be viewed and analysed easily. Additionally, it should be somewhat futureproof, regarding possible new innovations and applications of B-WIM technology.

3.2 Vehicle data presentation

Current SiWIM format shown in Table 9 offers a good basis for the new standard. The following values from the SiWIM are retained to the new standardised format:

- timestamp,
- warning flags / error code,
- lane (as modified),
- speed,
- number of axles,
- vehicle class,
- axle group,
- GVW,
- axle weights,
- total axle distance,
- axle spacing, and
- temperature.

The presentation of these values is mostly the same as in SiWIM with few exceptions mentioned below. Most of the values are self-explanatory and their exact way of presentation is described in Table 10.

The lane value is slightly modified from the original SiWIM presentation. In SiWIM, the lanes are numbered from one to onwards. This may cause confusion if the lane directions are not known or if there is more than one lane per direction. Thus, in the new standard, the lanes will be noted with A1, A2, B1, B2, and so on. A and B in front of the number dictates the direction of the lanes. The letters are assigned so that the A lanes are for the direction going northbound and B lanes are for southbound. The numbers dictate the number of lanes going in the same direction, starting with the slow lane that is assigned as 1.

The vehicle classification is kept in the new standard regardless of the few issues that its implementation might have. As vehicle classification might be country-specific and change during the years, a situation can occur where multiple different vehicle classification sets are in use simultaneously. If the software utilises the vehicle classifications in the calculations,

the user should confirm which vehicle classification the software is using and use corresponding B-WIM data. If necessary, the user can modify and change the vehicle classes to correspond to the same specifications as used in the software. This can be done as the vehicle classification is based on the axle spacing values and thus can be calculated from the B-WIM data itself.

Additionally, following values, not used in SiWIM format, are added to the new format:

- vehicle ID,
- dynamic amplification factor (DAF),
- wheel type,
- lateral offset, and
- reserve for future additions.

The vehicle ID is added to identify each vehicle. It can be used to connect additional data such as pictures or strains to the corresponding vehicles. The ID number is running number and should start from 1.

The dynamic amplification factor displays the difference between static vehicle weight and dynamic force. As the road surface, bridge type, multi-vehicle presence, and other environmental factors affect the DAF, it is not fully a vehicle-specific value. Thus, applying it directly from the measurement site to another site may induce inaccuracies to the analyses. Nevertheless, it can still reveal relevant information from the bridge site and the vehicles themselves thus it is chosen to be added to the new standardised format.

The wheel type is a significant part of the area on which the truck weight is affecting the pavement. In some applications, such as ESAL calculations, asphalt designing, and in some degree fatigue analysis, the area of the forces might have notable differences on the calculation outcome. Typical B-WIM systems cannot measure the wheel type of the axles thus this value might not be always available. However, in SiWIM system this can be estimated on some degree by using the axle configurations and statistical data on typical truck wheel settings for different vehicle classes. Additionally, in some WIM systems, the measurement of wheel types is possible thus this addition is seen necessary in the new standard. Moreover, identifying the wheel types from pictures may with the current development of image analysis and recognition become feasible in the near future. One option is to classify the wheel types according to SFS-EN 1991-2 table 4.8 (2004). Addition to the three types presented in the table, wheel type D is added to denote other not specified wheel types.

Similarly, as with wheel type, the lateral offset is not measurable with typical B-WIM systems. It can be measured with a special axle detector arrangement on the lane. Some researchers have also experimented measuring it with non-road methods (O'Brien et al. 2012). In WIM systems, the measurement of lateral offset is more straight forward and typical. Moreover, like with wheel type, measurement of lateral offset might become more common with advanced image analysis implementation. The lateral offset can be useful in multiple different B-WIM analysis thus it is included in the new standardised format.

The development of B-WIM systems might bring new measurable values that can be useful in B-WIM applications in future. Thus, reserved space is left to the end of the other values to accommodate possible future additions. As the sequence of the original data fields stays

the same, there should be fewer problems when data with extra values is used in software that has not been changed to account these new values.

The format for the proposed standardised presentation of B-WIM data is shown in Table 10. For the error code, a value of 0 should be used when no error code is present. For other data fields, a value of “null” should be used when data is not available. The value “null” is recommended instead of zero as in some cases the number 0 can be interpreted as a value of the field instead of a mark that the data is not available for this field e.g. temperature value of 0 can be read as zero degree temperature or no temperature available mark.

Table 10. Proposed standardised presentation for B-WIM data.

Column	Data	Unit	Note
1	Vehicle ID		
2	Timestamp		Format: YYYY-MM-DD-HH-MM-SS-mmm
3	Error code		Specified by measurement software. Default is 0
4	T	[°C]	Temperature
5	Lane		Marked as A1, A2, B1, B2, and so on. A for the northbound lanes and B for the southbound.
6	DAF		Dynamic Amplification Factor
7	v	[m/s]	Vehicle speed
8	Lateral offset	[m]	Lateral offset of the vehicle
9	Vehicle class		
10	N		Number of axles in the vehicle
11	Axle composition		Shows bogie types, e.g. semitrailer would be 113
12	Wheel types		Wheel types A, B, C according to SFS-EN 1991-2. D for other wheel types.
13	A _{GVW}	[kN]	Gross Vehicle Weight
13+1	A ₁	[kN]	Axle 1 weight
⋮	⋮	⋮	⋮
13+N	A _N	[kN]	Axle N weight
14+N	D _{TOT}	[m]	Total axle spacing from first axle to the last
15+N	D ₁	[m]	Distance/spacing between axle 1 and 2
⋮	⋮	⋮	⋮
13+2N	D _{N-1}	[m]	Distance/spacing between axle N-1 and N
14+2N	Reserve for future		If needed, additional values can be added here

As for the file format of the data, the Comma Separated Value (.csv) is proposed to be used. A sample from the proposed format as CSV file can be seen in Figure 29. The CSV is a widely used method to present tabulated data and is supported in most of the spreadsheet programs and programming languages. It is simple to implement and can be easily understood even in the text format. The disadvantage of using CSV is that it has no widely agreed specification thus there might be differences in its implementation.

Since the lack of widely agreed guidelines, few rules for the use of CSV in the standardised format is proposed:

- A semicolon is used as the delimiter between the data fields. The comma is used as decimal separator.
- The first row is reserved for headers line which describes the information in the columns.
- Each vehicle record is presented in a separate row.
- In CSV files, the number of columns should be constant for every row, thus empty fields/semicolons are added after the vehicle data to even out all the rows. Every row should have a total of 100 columns.

Figure 29. Sample from the CSV file.

The file name should state the measurement site, country, year of the measurements and running measurement number (see Figure 29). This naming principle would help making the different measurements easily recognisable and additionally provide extra information in cases where only the vehicle measurement file is available.

3.3 Other data

In previous section 3.2, the new presentation for the standardised vehicle data was proposed. The data presented in Table 10 consist most of the information of the vehicles but still, many other crucial data from the measured bridge, calibrations, accuracy, and other properties are left out. These could be presented in the same file with the vehicle data, but this would increase the complexity of it and complicate its readability and parsing in software. Thus, in the new standard an additional file is proposed to show the following information:

- type of B-WIM (or WIM) measurement,
- measurement site location,
- bridge properties and dimensions,
- measurement duration,
- calibration procedure and results,
- accuracy class,
- limits set for the measurement,
- lane descriptions, and
- bridge influence line and girder distribution factor.

The data is proposed to be presented in a document style file, such as Office Open XML (.docx), as it would make it easy to read and use. Document styled file could make the automatic data reading from the file quite complicated, but as there is not much numerical data proposed to be presented in the file, the data can also be easily added manually to the

software if needed. Similarly, as with the vehicle data, the file name should include the measurement site, country, year of the measurements, and running measurement number. The more specific format of this file is not determined in this thesis as only the vehicle data specific format is the main interest.

Additionally, other vehicle-specific data, such as pictures from the measured vehicles or the strain sensor data from the vehicle crossing, can be presented in a separate file. The data in these files is connected to the measured vehicle data by using the vehicle id number. The format and data presentation inside the files should be separately agreed if such data is included.

4 Case analysis

To demonstrate the benefits of standardised and extensive B-WIM database, a case study is conducted for the Lillholmen bridge. The Lillholmen bridge has a bascule bridge section with an orthotropic steel deck. In the study, a fatigue analysis is done by using a fatigue calculation software created as part of this thesis and by using Eurocode fatigue load model 4 (FLM 4). Results from the calculation software are analysed and compared to the ones determined according to the Eurocodes. Multiple different traffic compositions measured from various bridge sites in Finland are used and compared with each other.

The effects of new traffic regulations are also inspected as part of the case study. A site with yearly B-WIM measurements is selected and the fatigue damage is calculated with each year's data. The data and results for damage are then analysed, and the conclusions for the effects of the new traffic regulations for fatigue damage are made.

4.1 Case bridge

Lillholmen bridge site is located on a small local road in the Turku archipelago close to the town of Parainen in Finland. Currently, an old bascule bridge is located at the site but due to its old age and irreparable damage, a new bridge has been designed to replace the old one. The new bridge has a designed total length of 245 metres and is consisting of 9 spans (Figure 30). The bridge consists of two continuous prestressed concrete girder bridges and one 25 metres long bascule bridge section with an orthotropic steel deck. This case analysis focuses on the bascule bridge section thus from this point onwards the bascule bridge section is referred to as the Lillholmen bridge.

Figure 30. New Lillholmen bridge complex (PONTEK 2017).

The bridge crosses a busy 2,1 metres deep waterway, which is used mainly by small boats and occasionally larger sailboats. Previously the clearance on the bascule bridge was only 1,7 metres thus the bridge was required to open frequently which, on the other hand, caused notable delays for the road users. In the new design, the bridge has designed clearance of 6 metres decreasing the need to open the bridge, but still allowing large sailboats to use the waterway by lifting the bridge. (Lindroos n.d.)

The Lillholmen bridge length is 22,5 metres, and the bridge width is 8,9 metres (Figure 31 and Figure 32). The openable span is 18,25 metres. The bridge deck is opened by two hydraulic cylinders, attached 3,0 metres from swivel joint. The deck plate thickness is 16 mm and the crossbeam webs have cope holes for longitudinal deck plate stiffeners (Figure 32).

Figure 31. Side cut from the bridge (PONTEK 2017).

Figure 32. Bridge cross-section and longitudinal deck stiffener detail (PONTEK 2017).

4.2 Traffic on the site

As the bridge is located on a small local road, the heavy vehicle traffic on the bridge is scarce. A project evaluation has been done by Sitowise Ltd (Lindroos n.d.) to evaluate the viability of the new bridge and both current and future traffic. In the evaluation, the total traffic on the road has been estimated to be approximately 1000 vehicles per day from which around 3-4% are heavy vehicles. This would indicate approximately 11000-15000 heavy vehicles per year in total. The increase in traffic was evaluated to be quite small, and for heavy vehicle traffic, it was predicted that the traffic would decrease to 30 heavy vehicles per day in the year 2040.

As the estimation of heavy vehicle traffic is considerably smaller than Eurocode estimation of 50000 heavy vehicles per year and per lane for local roads (Figure 33), the client decided to use a smaller value of 10000 heavy vehicles per year and per lane in the fatigue calculations. This estimate is somewhat more numerous than Sitowise's project evaluation estimation. The 10000 heavy vehicles per year and per lane proposed by the designer is chosen for the traffic volume in the calculations.

4.3 Fatigue design according to Eurocode

Calculating exact fatigue damage is a challenging task. There are multiple different factors that notably affect the occurrence of damage and its propagation. Variables, such as micro scale material properties and structure loading spectrum are difficult to determine thus series of simplified methods based on measured data are used in Eurocode to calculate fatigue damage.

For calculating the traffic loads on the bridge, Eurocode SFS-EN 1991-2 (2004) has five different fatigue load models which are referred to as FLM 1...FLM 5. In addition, national annexes can be used to specify the adaptation of these load models and fatigue calculations.

In Finland, non-contradictory complementary Eurocode guidance NCCI 1 (FTA 2017) is used to further specify these load models and their usage in Finnish bridges.

FLM 1 and FLM 2 are mainly intended to be used to check if the fatigue life of the bridge can be considered unlimited. In FLM 1 the load configuration is similar to the Load Model 1, with the values of axle loads multiplied factor of 0,7 and uniformly distributed load with a factor of 0,3. FLM 2 consists of a set of idealised lorries. The usage of FLM 2 is prohibited in Finland as stated in NCCI 1, as the vehicle types in FLM 2 do not represent typical Finnish vehicles well enough.

FLM 3 to FLM 5 are intended to be used to calculate the estimated fatigue life for the bridge. FLM 3 consists of 4-axle vehicle with axle weight of 120kN and axle spacing of 1,2 + 6,0 + 1,2 metres. If relevant, a second vehicle with 36kN axle weights can be used. The spacing between these vehicles should be at least 40 metres. NCCI 1 recommends using this fatigue load model to calculate the fatigue life of the bridges in Finland. FLM 4 consists of sets of standardised lorries and is generally thought to be more accurate than FLM 3. The use of FLM 4 is further explained in section 4.3.1. FLM 5 consists of actual traffic data that is applied to the fatigue calculations. SFS-EN 1991-2 Annex B further describes the use of FLM 5. In the annex, it is stated that dynamic amplification factor ϕ_{fat} , must be used for static axle weight data. A value of $\phi_{fat} = 1,2$ can be used when the road surface condition is expected to be of good quality, and the value of $\phi_{fat} = 1,4$ when the road surface is expected to be of medium quality.

Material fatigue strengths can be described with S-N curves (see Figure 26 in section 2.5.1.2). As stress states and residual stresses due to forming and welding are usually quite complicated to calculate for complex joints and details, a series of structural details with corresponding detail categories are listed in Eurocode 1993-1-9 (2005). These detail categories can be used to choose the corresponding S-N curve, for the detail.

4.3.1 Fatigue Load Model 4

As mentioned above, Fatigue Load Model 4 consists of a set of standard lorries. These lorries are presented in Figure 33. Even though FLM 4 is usually considered more accurate than FLM 3 its use in Finland is restricted. The vehicles in FLM 4 do not represent typical lorries used in Finnish traffic well thus the usage of it must be agreed with authority. In NCCI 1 (2017) it is stated that using FLM 4 is justified in fatigue design of steel deck details, e.g. orthotropic steel decks. The authority can further specify if changes to the traffic types or equivalent loads are needed.

The three different traffic types are determined for local, medium distance and long distance traffic. A specific wheel type is assigned for every wheel and these can be used for details where the different wheel types cause different stress ranges. Further definitions for the axle widths and different wheel types are stated in Figure 33. The total vehicles N_{obs} per year and per lane can be estimated with different traffic categories and the total number of vehicles for the whole carriageway can be estimated as $\sum N_{obs}$. Other traffic estimations and interpolation of Figure 33 values can be used to estimate the yearly traffic

VEHICLE TYPE			TRAFFIC TYPE			
1	2	3	4	5	6	7
			Long distance Lorry percentage	Medium distance Lorry percentage	Local traffic Lorry percentage	Wheel type
LORRY	Axle spacing (m)	Equivalent axle loads (kN)
4,5	70 130	20,0	40,0	80,0	A B
4,20 1,30	70 120 120	5,0	10,0	5,0	A B B
3,20 5,20 1,30 1,30	70 150 90 90 90	50,0	30,0	5,0	A B C C C
3,40 6,00 1,80	70 140 90 90	15,0	15,0	5,0	A B B B
4,80 3,60 4,40 1,30	70 130 90 80 80	10,0	5,0	5,0	A B C C C

WHEEL/AXLE TYPE	GEOMETRICAL DEFINITION
A
B
C

Traffic categories		N _{obs} per year and per slow lane
1	Roads and motorways with 2 or more lanes per direction with high flow rates of lorries	2,0 × 10 ⁶
2	Roads and motorways with medium flow rates of lorries	0,5 × 10 ⁶
3	Main roads with low flow rates of lorries	0,125 × 10 ⁶
4	Local roads with low flow rates of lorries	0,05 × 10 ⁶

Figure 33. Set of equivalent lorries (left); definition of wheels and axles (top right); and traffic categories by number of heavy vehicles per year and per slow lane (bottom right) (SFS-EN 1991-2, 2004).

In calculations, every vehicle is considered to cross the bridge in the absence of other vehicles. Based on the axle weights and axle spacing the stress range spectrum can be calculated for each vehicle. As already discussed in chapter 2.5.1.2, a Rainflow or Reservoir counting methods can be used to determine the number of stress cycles and respective ranges per vehicle. The total number of stress cycles can be then calculated by multiplying those with the number of vehicles of chosen traffic composition. The cumulative fatigue damage from these vehicles can be then found out by utilising the S-N curve and Miner's rule.

4.3.2 Detail categories for orthotropic steel deck

Orthotropic steel deck assembly consists of multiple steel parts usually connected with welds. Due to the complex geometry and welding effects, the exact fatigue strength calculations for orthotropic steel decks are complicated. Eurocode offers a list for the critical regions of steel decks to determine the detail category of these regions. These are listed in Eurocode SFS-EN 1993-2 table 9.8 (2007). Table 11 shows these detail categories and corresponding pictures of the regions. Further details for these regions can be found from SFS-EN 1993-1-9 (2005).

Table 11. Detail categories for fatigue assessments for critical regions of steel deck.

Fatigue details SFS-EN 1993-2	Critical region	Detail	Detail to SFS-EN 1993-1-9	Detail category
<p>Figure 9.1:</p> <p>1 region 1 2 region 2 3 region 3 4 region 4 (splice) 5 region 5</p>	1	Deckplate stressed longitudinally at transverse fillet welds, see Figure 9.1	Table 8.4 detail 8	71
<p>Figure 9.2:</p> <p>1 butt weld 2 tack weld continuous along the full length of backing strip</p>	2	Deckplate stressed longitudinally at welded stringer-to-deckplate connection, see Figure 9.1	Table 8.2 detail 6	100
			Table 8.3 detail 9	80
	3	Hollow section stiffener at stiffener-crossbeam connection, see Figure 9.1	Table 8.8 detail 1	80
<p>Figure 9.4:</p>	4	Splice of stiffeners with splice plates and metallic backing strips, see Figure 9.2	Table 8.8 detail 4	71
	5	Free edges of cope holes in webs of webs of crossbeams around soffits of stiffeners, see Figure 9.4	Table 8.8 detail 6	112

4.3.3 Stress range from FEM model

During the design of the Lillholmen bridge, a FEM model Figure 34 was made by the designer with ROBOT structural analysis software to evaluate the behaviour of the bridge. The stress spectra for the critical regions of the orthotropic deck was also evaluated in the same model. During the modelling a few assumptions and simplifications were made:

- The stresses from the wheels were expected to divide in 1:1 ratio trough the asphalt layer thus additional 2*60mm were added to the Eurocode wheel lengths (Figure 33), increasing the total wheel lengths up to 440mm. The widths were not modified to create conservatism to the calculations.
- The modelled wheel weight was set as 50kN (100kN axle).
- It was assumed that the different axles do not interfere with each other denoting that one wheel directly caused one stress cycle. Thus, the influence line or stress spectra for the vehicles was not necessary to calculate.
- The most critical transversal wheel path was chosen when stress ranges were calculated, and every wheel was expected to cross the bridge on that path creating additional conservatism to the calculations.

Figure 34. ROBOT FEM model from above and below (PONTEK 2017).

The assumption that axles do not interfere with each other creates inaccuracy to the fatigue damage results. Even though the influence area that affects the detail is rather small, the spacing of double and triple axles are still minute enough to cause notable combined stress effects, which increases the maximum stress ranges and creates more complex stress cycle histories in the details. Unfortunately, more specific results and analysis were not available for the writer of this thesis, what was one reason to make this simplification. However, the main goal of this case study is to present the benefits of using standardised B-WIM data, thus calculation of the absolute fatigue life of the bridge is not the goal, but rather the comparison between multiple different B-WIM traffic and FLM4, thus this kind of simplification was considered justified. With these simplifications, the stress ranges for every critical region and every wheel type was obtained. These stresses are shown in Table 12 with corresponding detail category.

Table 12. Stress ranges for different wheel types.

Critical region	Detail category $\Delta\sigma_c$	Stress component	Wheel type A $\Delta\sigma_{pA}$ (MPa)	Wheel type B $\Delta\sigma_{pB}$ (MPa)	Wheel type C $\Delta\sigma_{pC}$ (MPa)
1	71	sigmaX, max-min	5,7	4,6	5,6
2a	100	sigmaX, max-min	15,5	13,2	15,6
2b	80	sigmaX, max-min	31,8	18,8	29
3	80	sigmaX, max-min	33,6	23,1	31,7
4	71	sigmaX, max-min	40,2	32,0	38,9
5	112	sigma1-sigma2	54,7	37,5	52,1

4.3.4 Fatigue calculations and results

To calculate the fatigue damage according to Eurocode FLM 4, Mathcad software is used. A calculation sheet is created in the software, which can calculate the fatigue damage from starting data and can also present damage accumulations for different wheel types and axles. Using Mathcad software allows easy modification to the starting data and calculation processes. The calculation sheet for critical region A4 can be found in Appendix 1. Additionally, other calculations were done utilising the same calculation sheet but from these only results will be shown.

The calculation process is divided into 4 different steps to provide the readers with a better understanding of the calculation process:

- **Step 1:** The starting data is inserted into the calculation sheet. The stress ranges for different wheels, as seen in Table 12, are obtained from the FEM model and the detail category is taken according to Table 11. For partial factor for fatigue load γ_{FF} , the recommended value of 1,0 is used. For material safety factor γ_{MF} , the value of 1,35 is chosen according to the safe life approach of SFS-EN1993-1-9 (2005). The local traffic is used in the calculations and as for traffic density, the designer suggested 10000 vehicles per year and per lane is used. An additional amplification factor $\Delta\phi_{fat}$ is calculated for the critical regions due to expansion joint being close to the areas (SFS-EN 1991-2 4.6.1 (6) (2004)). As all of the stress peaks for critical regions are at least 2 metres away from the expansion joint, an additional amplification factor of $\Delta\phi_{fat} = 1,2$ is obtained.
- **Step 2:** The corresponding stress ranges and total numbers for every axle-wheel combination are calculated. As the model was assumed to be linear elastic, the stress ranges can be multiplied with load factors. These factors are obtained by dividing equivalent axle loads (Figure 33) with reference axle load used in FEM modelling.
- **Step 3:** The cycles to failure are calculated for every axle-wheel combination using the corresponding design detail category. The cycles to failure are obtained by using Eurocode's trilinear S-N curve (Figure 26), with slopes of $m=3$ and $m=5$. For the unlimited fatigue cycles, the cycles to failure was set as an arbitrarily large number ($1*10^{20}$).
- **Step 4:** The total fatigue damage is calculated by using Miner's rule (equation (11)). Corresponding damage is also calculated for every wheel type and every axle type.

Results for Area 4 and other details are shown in Table 13. Area 4 is chosen as an example in Appendix 1 as it produced the highest fatigue damage thus being critical designing detail in fatigue perspective. Additionally, Area 2b is chosen for comparison as it has large differences between the stress ranges caused by wheel type A and B. The effects of this are further elaborated in section 4.5.2. Accumulated damage for other traffic types are calculated as well. Fatigue damage was also calculated for reference detail which has a stress range of 50 MPa for every wheel type. This includes the additional amplification factor. The additional detail is for comparison purposes only as it neglects the effects of different wheel composition of FLM 4 and B-WIM data. The detail category for the reference detail was set to 71. The local, medium distance, and long distance traffic noted in Table 13 are corresponding to the ones in Figure 33 (SFS-EN1991-2).

Table 13. Damage accumulations (for 10000 heavy vehicle per year).

	Traffic	A	B	C	1	2	3	Total
Area 4	Local	0,1005	0,4679	0,0676	0,5362	0,0615	0,0382	0,635
	Medium	0,1005	0,5707	0,2587	0,5828	0,1177	0,2294	0,9299
	Long	0,1005	0,6043	0,441	0,6628	0,1007	0,3823	1,1458
Area 2b	Local	0,0171	0,0299	0,0097	0,0471	0,0039	0,0057	0,0567
	Medium	0,0171	0,0387	0,0382	0,0541	0,0058	0,0342	0,094
	Long	0,0171	0,0439	0,065	0,063	0,006	0,057	0,1261
Reference detail	Local	0,1202	1,0393	0,0846	1,0697	0,1276	0,047	1,244
	Medium	0,1202	1,2791	0,3195	1,1725	0,2644	0,2819	1,719
	Long	0,1202	1,3532	0,5451	1,3366	0,2122	0,4698	2,019

4.4 Fatigue calculation software

To analyse the fatigue damage based on B-WIM data, a simple software was developed as part of this thesis. The software was coded by using Python programming language. The software can process standardised B-WIM data and calculate fatigue damage according to the wheel specific stress ranges and user specified settings. It calculates fatigue damage by utilising Eurocode detail categories and S-N curves. It can then display the results for every wheel and axle type. Additionally, a simple graphical user interface was also developed to improve the user experience.

In Eurocode the FLM 5 is loosely defined. It consists of the direct application of recorded traffic data, which the use of B-WIM data could be interpreted as. The software also utilises S-N curve and Miner's rule which are also part of the FLM 5 calculations thus practically it could be said that the fatigue calculation software uses FLM 5 to calculate the damage. It is good to note that some simplifications are used in the software that may not be usually used when FLM 5 is used.

4.4.1 Software analysis process

This section goes through the basic analysis process of the software, allowing the readers to better understand the analysis methods and the simplifications made. The list of simplifications and their effects is further elaborated in section 4.4.2. The basic flowchart of the software analysis progress is shown in Figure 35.

Figure 35. Basic flowchart of fatigue analysis process of the software.

The first step in the analysis is to upload the B-WIM data to the software. The software reads the standardised B-WIM file, which in the case of this study is an Excel file and goes through every vehicle in the data file. The necessary information from the vehicles is uploaded to the software's vehicle list. Additional files can be added if data from multiple different

measurements is wanted to be used simultaneously. The vehicles from additional files are added to the list and the software will handle the combined data as one large data set.

To screen suitable B-WIM data and to evaluate traffic properties, a simple traffic analysis tool was added to the fatigue calculation software. The tool can count the number of different axle types in the data, create a vehicle type division similar as in Figure 33, and plot a histogram from axle weights. This tool is utilised in section 4.4.4 to evaluate the properties of different B-WIM traffic chosen for this case study.

The fatigue analysis part is started by running an axle sorting algorithm (see Figure 35, axle sorting). The algorithm goes through the vehicle list and sorts the vehicle's axle weights according to the axle types. The sorted axle weights are converted to wheel weights and a dynamic amplification factor is applied. Next, the wheel count for every axle type is counted with steps of 0,5 kN, signifying that every wheel weight is rounded up to the nearest number divisible by 0,5 kN. Thus, a chart for every axle type is obtained that dictates the number of axles every 0,5 kN. The steps in the process are small enough that the effects to the accuracy due to rounding in wheel weights is neglectable. The axle counts are then divided according to the wheel type chart and in total 9 brackets for wheel weights are obtained (3 wheel types x 3 axle types). The wheel counts are then multiplied with factor accounting user set service life and yearly reference traffic. The factor is obtained by dividing the yearly reference traffic with a total number of vehicles in the B-WIM data and multiplying it with the service life. In other words, this factor is used to multiply the wheel weight chart to obtain the total number of axles of every wheel-axle combination for the whole service life of the bridge. The wheel weights are converted to stress cycles by using user set wheel type-specific stress ranges. From this, a list with stress ranges and corresponding number of cycles for the whole service life of the bridge is obtained. The software then uses the S-N curve to obtain the corresponding cycles to failure for every stress range from which the fatigue damage for the different wheels and axle types are calculated by using Miner's rule. The damage from different wheel types or different axle types can be summed to obtain the total fatigue damage for the detail. Additionally, the fatigue damage percentage from the heaviest 1% and 10% of the axles in the B-WIM data is calculated. The results are shown in the result page accompanied by a histogram and cumulative graph from the total fatigue damage.

If B-WIM data in the proper format is available and all the starting parameters are known, the analysis process only takes a few minutes to run. With standardised B-WIM data, running multiple analysis with various traffic and settings is a simple and fast process. This enables easy comparison of how different traffic affect the chosen details. Moreover, by adjusting the starting parameters, comparison of different scenarios is also a swift process.

4.4.2 Limitations and simplifications in the software

Due to the scope of this case study and limitations with available data, some simplifications with fatigue calculations are made during the development of the software. These simplifications create some inaccuracies to the results. However, as mentioned before, the goal of this case study is not to obtain absolute fatigue life of the bridge, but rather show possibilities of using standardised B-WIM data and to create a comparison between this data and fatigue damage calculated according to FLM 4.

Similarly, as in FLM 4 calculations, it was assumed that every axle cause stress cycle independently from other axles. As mentioned previously this is expected to reduce the fatigue damage obtained from calculation. It is also assumed that the wheel path in transversal direction passes always over the same point. The point is chosen so that it causes the maximum stress range in transversal direction and, thus it causes conservatism to the results. These simplifications imply that the combined effects of two vehicles driving on separate lanes is not considered. This can cause large inaccuracies as the multi-vehicle presence scenarios tend to increase the stresses notably. On the other hand, in this specific case study, the area that affects the details is small thus the effects of multivehicle presence are also smaller. Additionally, the traffic on the bridge is sparse and the bridge length is rather short thus the probability for two heavy vehicles facing on the bridge at the same time is rather small.

In this case study, the stress ranges in studied details are dependent on the wheel types thus it is necessary to know the wheel types to obtain the correct results. Typical B-WIM systems are not able to determine wheel types from passing vehicles thus data from other source is used to assign wheel type for every axle (Table 15). The data used in the case study is obtained from axle mass research (Toikka, Virtala 2015). The process and data are presented in more detail in section 4.4.3. The data used was measured during 2013 and 2014 which makes it relatively old data especially due to the vehicle regulation changes. Also, the traffic on the measurement site affect the frequency of certain wheel types thus the data obtained is partly site-dependent. These factors cause some inaccuracies to the probability chart used in wheel assignment what, on the other hand, cause inaccuracies to the fatigue damage results.

The software only uses single-, double-, and triple-axle (or single, tandem and tridem axle) bogies in the fatigue calculations and disregards bogies with four or more axles in them. Bogies with more than three axles are usually special cases or wrongly identified vehicles and thus were not used. Usually, the number of these kinds of bogies was low in the used B-WIM data, thus the effects to the final results are not deemed to be relevant.

As the software uses the B-WIM data directly, it is prone to statistical errors and abnormalities in data. E.g. if an extremely heavy axle that in a statistical sense is only spotted once in a year happens to cross the bridge during the measurement period, the number of these vehicles can be multiple times larger in the software fatigue calculations than it would be in reality. For a seven-day measurement period with similar traffic volume as in the analysis, this would denote 52 times larger count of these axles compared to the reality. This same principle also applies backwards and underestimation of the number of heavy axles might occur. Using data directly can also cause problems with small data sets. In the software, the user can modify yearly heavy vehicle number to the wanted value. This will create a factor based on the inputted value and number of vehicles in the data set. For cases where the data set is small, e.g. short measurement period or quiet road, the importance of single vehicle is larger. Thus, errors or abnormal weights can cause large inaccuracies when small data sets are used.

To calculate the corresponding stress range for different weights, a linear elastic behaviour of the model is expected. The wheel stress ranges are inputted in the unit form of MPa/kN. These are multiplied with wheel weights to obtain corresponding stress range for the stress cycles. If the real-life behaviour of the detail is nonlinear, the linear elastic assumption will cause inaccuracy to the obtained results.

As most of these assumptions were also made in FLM 4 calculations, it is safe to assume that comparing these two results will still yield relevant results and show the differences when using B-WIM data, even though the absolute fatigue life results might not be correct.

4.4.3 Analysis settings

For the partial fatigue safety factor γ_{Ff} and material safety factor γ_{Mf} , the same values are used as in the FLM 4 calculations, which are 1,0 and 1,35 respectively. These safety factor values are used for all the analyses. An additional amplification factor $\Delta\phi_{fat} = 1,2$ was added to the wheel specific stress ranges due to the expansion joint proximity. Additionally, the axle weights are multiplied with dynamic amplification factor ϕ_{fat} as stated in SFS-EN 1991-2 Annex B (2004). A good road surface is assumed thus the value of $\phi_{fat} = 1,2$ is used. In total, the dynamic amplification factors are $1,2 * 1,2 = 1,44$.

B-WIM measurement systems are generally not able to record wheel types of passing vehicles. The available B-WIM data is no exception from this thus the wheel types are needed to be assigned for every axle. Research on this subject is scarce and no guides or codes are available that states how the wheel types should be assigned in measured traffic data. Thus, a probability chart based on the axle mass research (Toikka, Virtala 2015) is created. The research had three different wheel types divided according to the bogie type as seen in Table 14. From this table the proportion of wheel types for single-, double-, and triple-axle bogies are calculated, and these proportions are used to assign wheel types for B-WIM data in the software. In the axle mass research, the wheel types were divided into a truck and two trailer categories. In the probability chart, these three categories were combined into one as the data set in trailer 2 category was too small and differentiating these categories from each other in B-WIM data was deemed ineffective and too time consuming.

Table 14. Wheel type divided according to the bogie type (Toikka, Virtala 2015).

Vehicle/ Bogie type	Wheel type			Total
	Single wheel (A)	Dual wheel (B)	Supersingle (C)	
Truck	3164	3178	400	6742
1-axle	2415	627	11	3053
2-axles	589	2158	313	3060
3-axles	155	382	72	609
4-axles	5	11	4	20
Trailer 1⁽¹⁾	2106	1826	2994	6926
1-axle	22	127	34	183
2-axles	693	1346	1185	3224
3-axles	1388	313	1767	3468
4-axles	3	29	8	40
5-axles		5		5
6-axles		6		6
Trailer 2⁽²⁾	51	21	92	164
1-axle	1			1
2-axles		6	22	28
3-axles	50	15	70	135
Total	5321	5025	3486	13832

⁽¹⁾ Trailer of full trailer combinations (truck + one trailer)

⁽²⁾ Second/module trailer of module combinations (truck + semi/full trailer + module trailer)

Table 15 (left) shows the combined data set for the wheel types. From this data the wheel probability chart was calculated (Table 15 right). This data was inputted to the software and is used by default to calculate the wheel type probabilities. These values can still be modified if the user sees its necessary or more accurate data is available.

Table 15. Combined (left) wheel type table and proportion (right) of those.

Bogie type	Wheel type			Total
	A	B	C	
1-axle	2438	754	45	3237
2-axles	1282	3510	1520	6312
3-axles	1593	710	1909	4212
Total	5313	4973	3474	13761

Bogie type	Wheel type		
	A	B	C
1-axle	75,3%	23,3%	1,4%
2-axles	20,3%	55,6%	24,1%
3-axles	37,8%	16,9%	45,3%

A special “front tyre” setting was also developed, which improves the wheel type chart by making it more realistic. This setting was expected to decrease the fatigue damage notably but on average it only decreases the fatigue damage by a few percent. Nevertheless, as it is already implemented to the software and it still offers more realistic results, it is applied in the analyses. Pihlajamäki (2001) states that front axles are almost always equipped with a narrow single wheel. In the “front tyre” setting, this is considered, and every front axle wheel that is a single axle is set as single/narrow (A) wheel. After this, a new wheel probability chart is calculated where these front axles are subtracted. This increases the percentage of dual and supersingle wheels for single axle category. The dual and supersingle wheels usually cause lower stress ranges. When considering that the front axles are usually less loaded than other single axles and in the setting, the larger proportion of other single axles are less stressing dual or supersingle wheels, the total fatigue damage can be expected to decrease.

For stress ranges, detail categories, and yearly traffic the same values are used as in the FLM 4 calculations. For stress ranges, the results from Table 12 are divided by the 50 kN wheel weight and then multiplied with $\Delta\sigma_{fat}$ to obtain stress ranges per unit weight for the critical region.

4.4.4 Used B-WIM data

B-WIM data used in this analysis were the same data collected during the Finnish B-WIM measurements conducted by FTA (2018). The measurements were taken by Swedish company Trafikia. For the measurements, the SiWIM system was used.

Three different B-WIM measurement sites (Figure 36) are selected for the case study. These sites are Kaarina (road 180), which is used for local traffic, Kehä III (road 50), which is used for medium distance traffic, and Olhava (VT4 - E75/E8), which is used for long distance traffic. Additionally, Olhava is also used to analyse the changes caused by the new traffic regulations as yearly data is available from the site for years 2013 to 2018. Measurements data utilised in this case study is obtained from FTIA’s B-WIM measurement project and further information from the measurements and sites can be found from FTIA’s B-WIM report (2018). The traffic analysis module is used to plot histograms describing the axle weights for every B-WIM site in this study. A complete set of these histograms for every

site is presented in Appendix 2. A simple vehicle type classification as in Figure 33 was also done to help to compare the B-WIM data to Eurocode traffic types.

Figure 36. Three chosen B-WIM sites location.

The measurement period in all of the B-WIM measurements used in this case study was seven days. According to SFS-EN 1991-2 annex B (11) (2004) when using real traffic data, the measurements shorter than 7 days might need adjustment. Thus, the data should be acceptable in respect of measurement period length. In the measurements, the minimum weight, which is recorded, was set to 10 tons. This disregards a large number of lighter vehicles but should not affect the final results as these vehicles are light enough to not cross over the lower fatigue limit. The cycles below that limit are thought to have infinite fatigue life (see S-N curve in Figure 26). This can be seen in the damage histogram (Figure 42) where the damage caused by the axles lighter than 50 kN are practically non-existent.

4.4.4.1 Local traffic - Kaarina (lane 2)

Data from Kaarina measurement site is used to simulate the Eurocode's local traffic. The site is located on Turku archipelago ring road leading to the city of Parainen, where the Lillholmen bridge is also located. The traffic weights are quite divided between the lanes as there is a limestone quarry in Parainen. The traffic on lane 1 leading away from Parainen is heavier as the fully loaded trucks are leaving from the quarry and the traffic on lane 2 is lighter as the mostly empty trucks return back. This can be seen as a spike in low axle weights in the B-WIM data as presented in Figure 36 a) and b). Lane 2 is selected to simulate local traffic as the vehicle and axle weights on the lane are relatively light partly due to the empty vehicles. For Kaarina site, the data from the year 2016 is used. The data set is quite small thus it is more prone to errors compared to other data sets. Measurement data from Kaarina are also available from the year 2014 but it is not used with 2016 data as it is considered to be too close to the 2013 vehicle regulation change and thus is still on the transition phase.

Figure 37. Kaarina 2016 B-WIM data for a) lane 2 and b) lane 1.

The vehicle types seen in Figure 37 correspond to equivalent vehicles in Eurocode FLM 4 Figure 33. The difference between B-WIM traffic composition and Eurocode's local traffic is quite notable but this is mostly due different vehicle base in Finland and in central Europe and thus the categories are not comparable.

Additionally, the combination of lane 1 and lane 2 is used in the analysis. This combination is heavier due to the fully loaded truck on lane 1 thus this traffic is categorised as medium distance traffic. The data from year 2016 is applied.

4.4.4.2 Medium distance traffic – Kehä III (all lanes)

For second set of medium distance traffic, B-WIM data from Kehä III measurements is used. Kehä III is most outer ring road in Helsinki. The heavy vehicle traffic flow on the road is high and it is a mix of light, medium, and heavy vehicles, thus being a good choice to simulate the medium distance traffic. The data from all lanes to both West and East direction from years 2015 and 2017 is used (Figure 38). The front axles are presented separately in this figure thus the single axle category presents other single axles.

Figure 38. Traffic analysis from 2015 and 2017 for Kehä III in a) east direction b) west direction.

When comparing the vehicle types to ones in Figure 33, the traffic composition is again quite different. When comparing to Kaarina data, the percentage of vehicle types 3 and 4 are slightly larger. These vehicles are usually heavier which also indicates that Kehä III can be regarded heavier traffic than Kaarina lane 2 traffic.

4.4.4.3 Long distance traffic – Olhava (both lanes)

Olhava site was selected to simulate the long-distance traffic. Olhava is located on main road E75/E8, between Oulu and Kemi. The heavy vehicle traffic flow on the site is not too high but the weights of these vehicles are notably larger compared to Kaarina or Kehä III. The data from the years 2015, 2017, and 2018 is used in the analysis (Figure 39).

Figure 39. Traffic analysis from 2015, 2017, and 2018 for Olhava in a) north b) south direction.

In Olhava, lane 1 towards the north (Kemi) has much heavier traffic than in lane 2 towards the south (Oulu). A similar effect was also present as in Kaarina. Lane 1 has more fully loaded vehicles and lane 2 has more empty ones. The reasons for this phenomenon was not mentioned in the measurements.

Figure 40. Olhava 2014 axle data a) for single axes on each day (FTA 2018, measurement data) b) histogram.

Additionally, B-WIM data from Olhava site is also applied to illustrate the effects of 2013 vehicle regulations changes. For this analysis, data from the years 2013 to 2018 is used. It is good to note that data from the years 2014 and 2016 has some errors thus the results from these years should be considered slightly wrong. In the year 2014 data, a measurement error was noticed in the measurement system. Due to unknown reason, front axle weights were locked or capped to around 7.5 tons. This is well seen in Figure 40. During the year 2016, a

construction site was located on the same road which decreased the traffic volumes at the measurement point. This was suspected to be due to heavy vehicles avoiding the road constructions and taking a detour.

4.4.5 Analysis results

The settings and data described are set in the software and the fatigue damage are calculated for the selected details. The software calculates total fatigue damage, damage caused by each wheel type, and damage caused by each bogie type. Additionally, a histogram (Figure 41) and cumulative graph (Figure 42) of the fatigue damage versus axle weights are plotted. The axle weights presented in graphs are true axle weights without a dynamic amplification factor. The damage caused by the top 1% and top 10% of the heaviest axles are marked to the cumulative graph, and also to the result tables of the details. The cumulative damage and damage histograms for every area and traffic are presented in Appendix 3.

Figure 41. Cumulative damage for Area 4 with Kaarina lane 2 B-WIM data.

4.4.5.1 Detailed results

The stress ranges from Table 12, are divided by 50kN and then multiplied with the additional amplification factor. The obtained unit stress ranges; $\Delta\sigma_{uA} = 0,965$ MPa/kN, $\Delta\sigma_{uB} = 0,768$ MPa/kN and $\Delta\sigma_{uC} = 0,934$ MPa/kN, for Area 4 are inputted to the software. Results for the Area 4 fatigue damage are shown in Table 16.

Table 16. Fatigue damage for Area 4 with different B-WIM traffic.

B-WIM site	Wheel type			Bogie type			Total	Heaviest	
	A	B	C	1	2	3		1%	10%
Kaarina lane 2	0,2998	0,1058	0,0941	0,2578	0,1643	0,0776	0,4996	6,97%	43,54%
Kehä III	0,3100	0,1187	0,1126	0,2608	0,1744	0,1061	0,5413	6,41%	40,12%
Kaarina lane 1&2	0,4215	0,1902	0,1739	0,3291	0,3130	0,1437	0,7857	5,63%	33,65%
Olhava	0,5963	0,2350	0,2944	0,3966	0,3773	0,3518	1,1257	5,36%	30,14%

Figure 42. Damage frequency (percentage) for corresponding axle weights a) Kaarina lane 2, b) Kehä III, c) Kaarina lane 1&2, and d) Olhava.

In Figure 42 the fatigue damage curve shows the damage percentage versus axle weights. For Kaarina and Olhava, the peaks in the damage can be seen around 75-100 kN. When looking at the axle weight percentage, the peak for fully loaded axles can also be seen in the same weight range. The figure shows well how the bulk of the damage is mostly dependent on the heaviest axles and why the “front axle” setting did not affect the results notably. The graph for Kehä III stands out from others. As Kehä III has a large number of light axles the peak for fully loaded axles is not distinctive anymore. Still, the peak for damage is approximately at the same point where the fully loaded axles are and when this same figure is plotted separately for each bogie type, peaks for double- and triple-axle bogies can be seen close to the peak point of damage (Figure 43). An additional interesting observation from these graphs is that the number of axles crossing over the maximum allowable axle weight is rather few and thus damage from that region is also quite small. However, it is good to note, that the maximum allowed axle weight denotes the absolute maximum limit for a single axle from all the combinations (11,5 t), and for some combinations, e.g. double-axle bogie, the weight limit can be lower per axle.

Figure 43. Damage frequency (percentage) for corresponding axle weights and bogie types.

Similarly, as for Area 4, the calculated stress ranges are divided with 50kN and then multiplied with the additional amplification factor. Obtained unit stress ranges for Area 2b are $\Delta\sigma_{uA} = 0,763$ MPa/kN, $\Delta\sigma_{uB} = 0,451$ MPa/kN, and $\Delta\sigma_{uC} = 0,696$ MPa/kN. Fatigue damage results for Area 2b are shown in Table 17.

Table 17. Fatigue damage for Area 2b with different B-WIM traffic.

B-WIM site	Wheel type			Bogie type			Total	Heaviest	
	A	B	C	1	2	3		1%	10%
Kaarina lane 2	0,0722	0,0030	0,0185	0,0512	0,0260	0,0165	0,0937	8,90%	54,05%
Kehä III	0,0722	0,0030	0,0201	0,0497	0,0257	0,0198	0,0953	8,82%	50,94%
Kaarina lane 1&2	0,1109	0,0071	0,0376	0,0688	0,0548	0,0320	0,1556	7,03%	38,65%
Olhava	0,1534	0,0068	0,0568	0,0863	0,0595	0,0721	0,2180	6,78%	36,68%

For the additional reference detail, the stress range for every wheel is set as 50 MPa, which signifies that unit stress range type equals $\Delta\sigma_{uABC} = 1$ MPa/kN for all of them. The additional dynamic amplification factor is considered to be already included in the value. Fatigue damage results for this detail is shown in Table 18.

Table 18. Fatigue damage for reference detail with different B-WIM traffic.

B-WIM site	Bogie type			Total	Heaviest	
	1	2	3		1%	10%
Kaarina lane 2	0,3457	0,2759	0,1009	0,7225	6,80%	42,40%
Kehä III	0,3597	0,2981	0,1404	0,7982	6,53%	40,02%
Kaarina lane 1&2	0,4453	0,5131	0,1853	1,1437	5,37%	34,47%
Olhava	0,5218	0,6259	0,4556	1,6033	5,62%	31,11%

For the top 1% and 10% of the heaviest axles, the trend seems to be that for roads with lighter traffic the effects from heavier axles are larger. Reason for this is that the weight variation in the top 1% or 10% of the heaviest axles is larger for lighter traffic. As the fatigue damage increases eightfold times when load doubles, the impact of heaviest axles increases when compared to much lighter axles. Thus, for lighter traffic which has larger variation in heaviest vehicles the damage proportion of those vehicles is larger.

The results for Kehä III are lower than originally expected. The fatigue damage is still larger than the results for Kaarina lane 2 but notably smaller than results for both lanes for Kaarina. This suggests that either the traffic in Kehä III is lighter than expected or the traffic in Kaarina is heavier than expected. It is still good to note that damage values obtained are fixed to 10000 heavy vehicles per year for all locations. In reality, the traffic flow in Kehä III would be much larger compared to Kaarina and would thus be much more damaging.

4.4.5.2 Olhava 2013-2018 results and conclusions

The fatigue damage development for each year's traffic was inspected with Olhava site B-WIM data. Area 4 and reference detail were chosen for the analysis. The traffic flow was set as 10 000 heavy vehicles per year and per lane. Results for Area 4 are shown in Table 19 and for reference detail in Table 20. The years 2014 and 2016 are highlighted as the B-WIM data from these years has errors in it as said in section 4.4.4.3.

Table 19. Fatigue damage in Area 4 for Olhava from year 2013 to 2018.

Year	Wheel type			Bogie type			Total	Fatigue life	Difference to 2013
	A	B	C	1	2	3			
2013	0,5061	0,1947	0,1728	0,4214	0,3256	0,1266	0,8735	114,4	0 %
2014 ⁽¹⁾	0,5282	0,2339	0,2205	0,4003	0,4100	0,1724	0,9827	101,8	13 %
2015	0,5141	0,2305	0,2458	0,3612	0,3868	0,2424	0,9904	101,0	13 %
2016 ⁽²⁾	0,5016	0,1945	0,2086	0,3778	0,3143	0,2126	0,9047	110,5	4 %
2017	0,6326	0,2157	0,2863	0,4323	0,3456	0,3567	1,1346	88,14	30 %
2018	0,6492	0,2587	0,3547	0,4003	0,3970	0,4652	1,2626	79,20	45 %

⁽¹⁾ Error in B-WIM measurements

⁽²⁾ Construction work affected the traffic

Table 20. Fatigue damage in reference detail for Olhava from year 2013 to 2018.

Year	Wheel type			Bogie type			Total	Fatigue life	Difference to 2013
	A	B	C	1	2	3			
2013	0,5699	0,4808	0,2166	0,5539	0,5449	0,1685	1,2673	78,91	0 %
2014 ⁽¹⁾	0,5932	0,5651	0,2750	0,5288	0,6779	0,2266	1,4333	69,77	13 %
2015	0,5791	0,5556	0,3056	0,4857	0,6399	0,3147	1,4403	69,43	14 %
2016 ⁽²⁾	0,5651	0,4766	0,2606	0,4994	0,5252	0,2776	1,3023	76,79	3 %
2017	0,7092	0,5269	0,3561	0,5537	0,5759	0,4626	1,5922	62,81	26 %
2018	0,7282	0,6213	0,4401	0,5304	0,6581	0,6010	1,7895	55,88	41 %

⁽¹⁾ Error in B-WIM measurements

⁽²⁾ Construction work affected the traffic

In both details, a clear increase in total fatigue damage can be seen. This is due to the new heavy vehicle regulations placed into effect on 2013 which increased the maximum allowable loads. It has led to increased axle load what has increased fatigue damage. The increase has been gradual in past years as the transportation companies have been adapting to the new regulations with delay. If results from 2014 and 2016 are disregarded the increase in fatigue damage can be plotted as linear as presented in Figure 44. The increase in fatigue damage from 2013 to 2018 has been over 40% for these two details which is quite notable. The yearly increase in the damage has been approximately 7%.

Figure 44. Damage increase for the different axle types.

The new regulations have especially affected the triple axles. From Table 19 and Table 20, it can be seen that the damage caused by triple axles has increased notably. The number of triple-axle bogies has almost doubled from 2151 to 3939 bogies even though the total vehicle count has stayed pretty much the same. For total axles count, it would denote almost six times more axles. Also, the weights of triple axles have also increased notably. In Figure 45, a comparison is made between 2013 and 2018 and from it, the increase in both count and weight of the triple axles can easily be seen.

Figure 45. Olhava axle weight progression from year a) 2013 and b) 2018.

4.5 Result comparison

4.5.1 Area 4

Table 21 shows the comparison between FLM 4 and results obtained with B-WIM data. For local and medium distance traffic the total fatigue damage is in all cases smaller than corresponding damage calculated with FLM 4. This is expected as Eurocode should offer a conservative estimate. For long distance traffic, the estimations yielded by both methods are almost the same, but when comparing the damage from different wheel types or bogie types the differences are notable. The bolded values in the table represents the larger value when damage from B-WIM data is compared with FLM 4.

Table 21. Damage comparison for Area 4.

Traffic	Wheel type			Bogie type			Total	Diff.
	A	B	C	1	2	3		
Local								
FLM 4	0,1005	0,4679	0,0676	0,5362	0,0615	0,0382	0,6350	0%
Kaarina lane 2	0,2998	0,1058	0,0941	0,2578	0,1643	0,0776	0,4996	-21,3%
Medium distance								
FLM 4	0,1005	0,5707	0,2587	0,5828	0,1177	0,2294	0,9299	0%
Kehä III	0,3100	0,1187	0,1126	0,2608	0,1744	0,1061	0,5413	-41,8%
Kaarina lane 1&2	0,4215	0,1902	0,1739	0,3291	0,3130	0,1437	0,7857	-15,5%
Long distance								
FLM 4	0,1005	0,6043	0,4410	0,6628	0,1007	0,3823	1,1458	0%
Olhava	0,5963	0,2350	0,2944	0,3966	0,3773	0,3518	1,1257	-1,8%

When looking closer at the wheel types, a large difference can be seen between wheel type A and wheel type B. Figure 46 shows well the differences between wheel damage

proportions for FLM 4 and B-WIM data. For all the traffic types the FLM 4 tends to overestimate the damage from wheel type B and underestimate the damage from wheel type A. From Figure 33 it becomes apparent that in FLM 4 the wheel type A is only used for lighter front axles which do not correspond well with real traffic, as wheel type A is commonly used for other heavier single axles and it can also be found from double and triple bogies. In the case of wheel type B, the FLM 4 uses it on all the heaviest axles increasing its damage output notably.

Figure 46. Calculated wheel type fatigue damage in true damage (up) and in proportional damage (down).

A similar effect is apparent in single axles and double-axle bogies as well (Figure 47). Most of the heaviest axles in FLM 4 are set as single axles, which increase the damage output from those. Double bogies, on the other hand, are lighter and the frequency of them is lower decreasing their damage output.

For the actual traffic data, it seems that the damage proportions from different axle types do not have as drastic changes when moving to heavier traffic as in FLM 4 (Figure 47). The trend seems to be that damage proportion from triple axles increases and for single axles it decreases. As the wheel types are dependent on axle types, this same effect can be also seen in wheel type damage proportions (Figure 46).

Figure 47. Calculated axle fatigue damage in true damage (up) and in proportional damage (down).

The damage increase from the lightest traffic to heaviest was smaller in FLM 4 than in B-WIM. In FLM 4, the increase from local traffic to long distance traffic was 80% as in the analysis the difference was 125%. This implies that the scale between the local traffic and long distance traffic is larger in B-WIM data. The reason for this may be that the B-WIM traffic corresponding to the local traffic (Kaarina) was either relatively less damaging compared to the local traffic in FLM 4 or the traffic corresponding to long distance traffic (Olhava) was relatively more damaging. Either way, the damage differences between FLM 4 and B-WIM were higher in local traffic than in long distance traffic. This suggests that the FLM 4 tends to be somewhat more conservative for the local traffic/light traffic than for long distance traffic/heavy traffic. Similar kind of effect, where the increase in B-WIM traffic was larger, was also observed for other details.

4.5.2 Area 2b

In area 4 comparison, it was noted that FLM 4 tended to overestimate the fatigue damage of wheel type B and underestimate wheel type A. For this reason, Area 2b was also chosen for the evaluation as the differences in its stress ranges for wheel type A and B were largest. The comparison is presented in Table 22, where the fatigue damage results for FLM 4 are smaller for all the traffic when compared to corresponding B-WIM traffic. In safety perspective, this is a negative sign as Eurocode should offer a conservative estimate when compared to more accurate results.

The same trend of FLM 4 overestimating the wheel damage of type B and underestimating damage of wheel type A is clearly visible. For wheel type A and B, the FLM 4 overestimates

the damage by factor of 10 and underestimates it by factor of 8 when compared to the B-WIM results. The reasons behind this is same as in Area 4 with exception that the differences are amplified due to wheel stress range differences. This also true for the axle damage. Figure 48 and Figure 49 presents these differences well.

Table 22. Damage comparison for Area 2b.

Traffic	Wheel type			Bogie type			Total	Dif.
	A	B	C	1	2	3		
Local								
FLM 4	0,0171	0,0299	0,0097	0,0471	0,0039	0,0057	0,0567	0%
Kaarina lane 2	0,0722	0,0030	0,0185	0,0512	0,0260	0,0165	0,0937	65,3%
Medium distance								
FLM 4	0,0171	0,0387	0,0382	0,0541	0,0058	0,0342	0,0940	0%
Kehä III	0,0722	0,0030	0,0201	0,0497	0,0257	0,0198	0,0953	1,4%
Kaarina lane 1&2	0,1109	0,0071	0,0376	0,0688	0,0548	0,0320	0,1556	65,5%
Long distance								
FLM 4	0,0171	0,0439	0,0650	0,0630	0,0060	0,0570	0,1261	0%
Olhava	0,1534	0,0068	0,0568	0,0863	0,0595	0,0721	0,2180	72,9%

Figure 48. Calculated wheel type fatigue damage in true damage (up) and in proportional damage (down).

Figure 49. Calculated axle fatigue damage in true damage (up) and in proportional damage (down).

Similarly, as for the Area 4, the damage proportions for B-WIM data seems to vary much less between different traffic than for FLM 4. This applies to both wheel and axle type proportions damage. In measured data, the proportion of triple axles increases for heavier traffic. Again, this leads to an increased proportion in wheel type C, but for this detail, the change is quite small partly due to the smaller stress range for wheel type C.

For this case, the damage increase from local to long distance traffic is larger than for Area 4. In FLM 4, the increase is 122% and for analysis, it is 133%. On the other hand, for this detail, the differences in the increase are smaller but still similarly as in Area 4, the FLM 4 seems to yield relatively larger damage for the local traffic.

4.5.3 Reference detail

For the reference detail, the stress ranges for different wheels are set the same to neglect any effects due to different wheel probabilities. As wheel types are not in interest, fatigue damage from those is not presented in the results.

For this detail, the fatigue damage obtained with B-WIM data is, similarly as in Area 4, lower than damage obtained with FLM 4 (Table 23). The same trend with Olhava being relatively largest when compared to FLM 4 is apparent in this detail also. Similarly, as in other details, the axle specific damage is overestimated in the single axles and underestimated in the double-axle bogies by the FLM 4 (Figure 50). Again, the reason for this is the same as for Area 4.

Table 23. Damage comparison for reference detail.

Traffic	Bogie type			Total	dif.
	1	2	3		
Local					
FLM 4	1,0697	0,1276	0,0470	1,2440	0%
Kaarina lane 2	0,3457	0,2759	0,1009	0,7225	-41,9%
Medium distance					
FLM 4	1,1725	0,2644	0,2819	1,7190	0%
Kehä III	0,3597	0,2981	0,1404	0,7981	-53,6%
Kaarina lane 1 & 2	0,4453	0,5131	0,1853	1,1437	-33,5%
Long distance					
FLM 4	1,3366	0,2122	0,4698	2,0190	0%
Olhava	0,5218	0,6259	0,4556	1,6033	-20,6%

When comparing the fatigue damage differences between local traffic and long distance traffic, the largest difference between B-WIM and FLM 4 is obtained with this detail. For FLM 4 the difference between local and long distance traffic is only 62 % as for the B-WIM data the difference between Kaarina lane 2 and Olhava data is 122%. These increases are similar as observed in Area 4.

Figure 50. Calculated axle fatigue damage in true damage (up) and in proportional damage (down) for reference detail.

5 Summary and Conclusions

5.1 Conclusions and Contributions

The thesis goals were to propose a new standardised way to present B-WIM data and to demonstrate the benefits of said data with a case study, where fatigue analysis is conducted for an orthotropic bridge deck. These goals were achieved, and the new standardised way to present B-WIM data was proposed. Moreover, the benefits of said data were successfully demonstrated with the case study and developed fatigue calculation software. Additionally, during the study, various interesting points from the traffic and loading properties of the analysed data were discovered. All these points can be concluded as follows:

1. *A standardised data format for the B-WIM data was proposed and applications of said data in bridge engineering were evaluated in this thesis.* A new proposed format was developed based on the current formats in use and the interviews with Finnish Transport Infrastructure Agency and Trafikia. During the development of the new format, the usability of it in computer analyses and other applications was emphasised. The proposed format is presented in Table 10. However, it should be emphasised, that the format proposed in this thesis is just a starting point, and it may very well undergo multiple changes in the future as it is applied more in practice and the needs of the users become clearer. Nevertheless, the proposal is still seen as a good basis for the future development and as such, can provide a format to produce standardised B-WIM data, and offer a chance to develop software utilising the data in practical bridge engineering applications.
2. *The benefits of utilising standardised format for the B-WIM data were observed and confirmed in the case study.* The process of modifying the non-standardised B-WIM data to proper format was laborious and took a long time, but when the data was in a standardised format, the analysis process was simple to do and took only a few minutes to complete. This enabled effortless analysis and comparison of fatigue damage with various scenarios, details and traffic.
3. *A fatigue calculation software with simple traffic analysis tool was developed in this thesis.* The tool offered an easy basis to evaluate the trends in traffic. B-WIM data used in the case study was analysed with it and as a result, a few reoccurring patterns were discovered. For most cases, the single axle patterns could be divided into two groups, front axles and other single axles. The weight deviation in both groups followed the standard deviation rather well, but in the other single axles, the variance was notably larger. For double-axle bogies, the weight patterns were less clear being usually either bimodal or trimodal. The pattern depended mainly from the site, but one to three distinct peaks could usually be observed. In case of triple-axle bogies, most of the weight patterns were bimodal with peaks on the lower weights or heavy weights. These corresponded to empty axles and fully loaded axles respectively.
4. *From the case study results, it was noticed that there are some challenges with Eurocode fatigue load model 4 when it is used to calculate the fatigue life of details where the stress ranges are heavily dependent on the wheel types of the axles.* Large variations between FLM 4 and B-WIM calculated wheel type-specific fatigue damage was noticed. FLM 4 tended to overestimate the damage from the wheel type

B (Dual wheel) and underestimate the damage from wheel type A (single wheel), when compared to damage obtained with B-WIM data. Based on these findings the writer recommends special care when using FLM 4, especially in cases where the stress range from wheel type B is notably lower than from other wheel types.

5. *The fatigue damage difference between local traffic and long distance traffic tended to be larger with B-WIM traffic than FLM 4.* As a result, the FLM 4 tended to give relatively larger damage values for local traffic than for the long distance traffic when compared to the B-WIM analysis results. This suggests that FLM 4 can be expected to be somewhat more conservative for the local traffic than for the long distance traffic. Thus, using FLM 4 on roads with lighter traffic should be on the safer side and, on the other hand, cautions should be taken when applying FLM 4 in heavily trafficked roads in Finland.
6. *The B-WIM data from Olhava gave good insight into the effects of the new traffic regulations to fatigue damage.* From the year 2013 to 2018, the fatigue damage increase was observed to be approximately 40 % for this case study, which was almost solely contributed from the triple-axle bogies. The reason for this was the increase in the total number of triple-axle bogies and the increase in the average weight of those. Even though the fatigue damage increase cannot be generalised for all bridges in Finland, the increase has still been considerable enough to conclude that the fatigue life of many bridges may have decreased to some extent due to the new traffic regulations.

5.2 Future work

During the development of the proposed standardised data format, the vehicle-specific data was the main focus as it is the most crucial information in majority of the applications. In the thesis, the format of the other data was slightly covered but not fully focused on. For the proposed data format to further become a fully developed standard, additional work is required. Furthermore, the proposed data format may also need slight adjustments when the format is applied more in practice and the requirements of the users become clearer.

In the development of the fatigue calculation software for this thesis, multiple different simplifications and assumptions were made, which has left room for many various improvements and future developments. The software in its current state is still a prototype specific to this case study but with some improvements, it could be used as a basis for software capable of accurate fatigue life assessment of most typical bridges.

The major step to improve the calculation procedure would be to expand the analysis algorithm to account the whole vehicle instead of a single axle at the time. By utilising the influence line of the analysed bridge, the time stress history could be calculated more precisely leading to more accurate results. A similar addition could also be done in the transversal direction. The position of the vehicles will always vary somewhat on the lane and for local details, such as an orthotropic deck, it might notably affect the stress ranges. In later stage, the software could be expanded to accommodate multiple lanes with different traffics on a bridge deck. Additionally, stochastic simulations, such as Monte Carlo simulation, could be applied instead of current direct data utilisation, to further widen the applicability of the software.

In Olhava analysis, a clear increase in fatigue damage was observed due to the new traffic regulations. A similar increase can be expected on other bridges in Finland as well, what might lead to shortening fatigue life in many bridges, especially on the ones where the fatigue design is the governing design case. More specific research should be conducted to evaluate the actual damage increase and severity on bridges prone to fatigue damage.

Lastly, since a significant increase in data transfer and processing capabilities can be expected in the future, it is easy to see how the big data from traffic measurements can and will be more easily utilised on a larger scale than in the past. A certain level of standardisation in the process would expand the benefits of research and applications vastly, as every new set of traffic data could be easily run through the analysis tools developed previously by various researchers and vice versa, the newly developed analysis tools could easily utilise all the previously produced traffic data.

References

- Al-Qadi, I., Wang, H., Ouyang, Y., Grimmelsman, K. & Purdy, J. E., 2016. *LTBP Program's Literature Review on Weigh-in-Motion System*. McLean, USA: Office of Infrastructure Research and Development. 42 p. Report No: FHWA-HRT-16-024.
- ASTM E1318-09, 2017. *Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Methods*. West Conshohocken. USA: ASTM International. 18 p. Available at: [http://www.astm.org/cgi-bin/resolver.cgi?E1318-09\(2017\)](http://www.astm.org/cgi-bin/resolver.cgi?E1318-09(2017)). DOI: 10.1520/E1318-09R17.
- Chatterjee, P., O'Brien, E., Li, Y. & González, A., 2006. Wavelet domain analysis for identification of vehicle axles from bridge measurements. *Computers & Structures*, Vol. 84:28. p. 1792-1801. ISSN: 0045-7949.
- Council Directive (EU) 2015/719 of 29 April 2015 on *amending Council Directive 96/53/EC laying down for certain road vehicles circulating within the Community the maximum authorised dimensions in national and international traffic and the maximum authorised weights in international traffic*. [Cited 26 Aug. 2020] Available at: <http://data.europa.eu/eli/dir/2015/719/oj>.
- European Automobile Manufacturers Association, 2017. *EU Roadmap for Truck Platooning*. [Cited 31 Jul. 2020]. Available at: <https://www.acea.be/publications/article/infographic-eu-roadmap-for-truck-platooning>.
- Finnish Government Decree 407/2013 of 6 June 2013 on *vehicle's usage on roads*. [Cited 7 Jul. 2020]. Available at: <https://finlex.fi/fi/laki/alkup/2013/20130407>.
- Finnish Transport Agency, 2018. *Bridge WIM Overview Report: Year 2013-2017*. [Internet document]. Helsinki, Finland. Research reports of the Finnish Transport Agency 29/2018. [Cited Jun. 2020] Available at: https://julkaisut.vayla.fi/pdf8/lts_2018-29_bridge_wim_web.pdf. ISSN: 9789-523175495.
- González, A., Žnidarič, A., Casas, J. R., O'Brien, E. & et al., 2009. *EU FP6-ARCHES Deliverable D10: Recommendations on dynamic amplification allowance*, Brussels, Belgium: FEHRL. 150 p.
- Iso-Junno, T., 2017. *Jännevirran sillan väsymismitoitus mitatulla liikennekuormalla*. Master's Thesis. University of Oulu, Faculty of Technology. Oulu: 78 p.
- ISWIM – International Society for Weigh in Motion, n.d. *WIM application in Bridge Engineering*. [Cited 6 Aug. 2020]. Available at: <http://www.iswim.org/index.php?nm=3&nsm=3&lg=en>.
- Kalhuri, H., Makki Alamdari, M., Zhu, X., Samali, B. & Mustapha, S., 2017. Non-intrusive schemes for speed and axle identification in bridge-weigh-in-motion systems. *Measurement science & technology*, Vol. 28:2. No. 025102. ISSN: 0957-0233.

Kalin, J., Žnidarič, A. & Kreslin, M., 2015. Using weigh-in-motion data to determine bridge dynamic amplification factor. *MATEC Web of Conferences*. Vol. 24. No.02003. 8 p.

Law, S. S., Chan, T. H. T. & Zeng, Q. H., 1997. Moving force identification: A Time domain method. *Journal of Sound and Vibration*. Vol. 201:1. p. 1-22. ISSN: 0022-460X.

Law, S. S., Chan, T. H. T. & Zeng, Q. H., 1999. Moving Force Identification—A Frequency and Time Domains Analysis. *Journal of dynamic systems, measurement, and control*. Vol. 121:3. p. 394-401. ISSN: 0022-0434.

Lechner, B., Lieschnegg, M., Mariani, O., Pircher, M. & Fuchs, A., 2010. A wavelet-based bridge Weigh-in-Motion system. *International journal on smart sensing and intelligent systems*. Vol. 3:4. p. 573-591. ISSN: 1178-5608.

Liikennevirasto, 2015. *Siltojen kantavuuslaskentaohje*. [Internet document]. Helsinki, Finland. 61 p. Liikenneviraston ohjeita 36/2015. [Cited Jun. 2020]. Available at: https://julkaisut.vayla.fi/pdf8/lo_2015-36_siltojen_kantavuuslaskentaohje_web.pdf.

Lilja, H., 2018. Finnish experience on HCT- vehicles. *ITF Bridge Seminar*. [Powerpoint presentation]. Paris, France, 31 Jan - 1 Feb, 2018.

Lilja, H., 2020a. Senior Bridge Specialist. *Finnish Transport Infrastructure Agency*. Helsinki, PL 33, 00521, Väylävirasto. [Interview, 12 Jun. 2020].

Lilja, H. & Tirkkonen, T., 2020b. Specialists. *Finnish Transport Infrastructure Agency*. Helsinki, PL 33, 00521, Väylävirasto: [Interview, 2 Dec. 2020].

Lindroos, K., n.d. *Maantien 12029 parantaminen uusimalla Lillholmenin silta, Hankearviointi*. Espoo, Finland: Sitowise. [Cited 5 Nov. 2020]. Available at: https://vayla.fi/documents/25230764/0/16T-3_Mt12029_Lillholmen_hankearviointi.pdf/ab30b929-7d7e-4282-9049-76ba1f4fb172

Lydon, M., Taylor, S. E., Robinson, D., Mufti, A. & O'Brien, E., 2016. Recent developments in bridge weigh in motion (B-WIM). *Journal of Civil Structural Health Monitoring*. Vol. 6:1. p. 69-81. ISSN: 2190-5479.

Lydon, M., Robinson, D., Taylor, S., Amato, G., O'Brien, E. & Uddin, N., 2017. Improved axle detection for bridge weigh-in-motion systems using fiber optic sensors. *Journal of Civil Structural Health Monitoring*. Vol. 7:3. p. 325-332. ISSN: 2190-5452.

Mandić Ivanković, A., Skokandić, D., Žnidarič, A. & Kreslin, M., 2019. Bridge performance indicators based on traffic load monitoring. *Structure and Infrastructure Engineering*. Vol. 15:7. p. 899-911. ISSN: 1573-2479.

McNulty, P. & O'Brien, E., 2003. Testing of Bridge Weigh-In-Motion System in a Sub-Arctic Climate. *Journal of Testing and Evaluation*. Vol. 31:6. p. 1-10. ISSN: 0090-3973.

Moses, F., 1979. Weigh-in-motion system using instrumented bridges. *Journal of Transportation Engineering*. Vol. 105:3. p. 233-249.

NCCI 1, 2017. *Eurokoodin soveltamisohje: Siltojen kuormat ja suunnitteluperusteet - NCCI 1 (6.12.2017)*. [Internet document] Helsinki: Liikennevirasto. 75 p. [Cited 20 Dec. 2020]. Available at: <http://urn.fi/URN:978-952-317-486-3>. ISSN: 9789-523174863.

O'Brien, E., Žnidarič, A. & Dempsey, A. T., 1999. Comparison of two independently developed bridge Weigh-in-Motion systems. *International Journal of Heavy Vehicle Systems*. Vol. 6:1-4. p. 147-161. ISSN: 1744-232X.

O'Brien, E., Žnidarič, A., Baumgärtner Werner, González Arturo, McNulty Peter & et al., 2001. *WPI.2: Bridge WIM Systems*. Dublin, Ireland: University College Dublin. 100 p. Weighing-In-Motion of Axles and Vehicles for Europe (WAVE). ISBN: 961-90366-1-1.

O'Brien, E., Jehaes, S. & Jacob, B.(ed.), 2002. *Weigh-in-Motion of Road Vehicles*. Paris, France: LCPC. 83 p. Final Report of the COST 323 Action.

O'Brien, E., Quilligan, M. J. & Karoumi, R., 2006. Calculating an influence line from direct measurements. *Proceedings of the Institution of Civil Engineers-Bridge Engineering*. Vol. 159:1. p. 31-34. ISSN: 1478-4637.

O'Brien, E., Hajializadeh, D., Uddin, N., Robinson, D. & Opitz, R., 2012. Strategies for axle detection in bridge Weigh-in-Motion systems. In: *6th International Conference on Weigh-In-Motion (ICWIM 6)*. Dallas, Texas, USA. 4-7 June 2012.

O'Connor C. & Chan Tommy, H. T., 1988. Dynamic Wheel Loads From Bridge Strains. *Journal of Structural Engineering*. Vol. 114:8. p. 1703-1723. DOI: 10.1061/(ASCE)0733-9445(1988)114:8(1703).

Office of Highway Policy Information, 2018. WIM Site Selection, Design, and Installation Guide. *Weigh-in-Motion Pocket Guide*. Part 2. Washington, D.C., USA: Federal Highway Administration. Available at: https://www.fhwa.dot.gov/policyinformation/knowledgecenter/wim_guide/.

Ojio, T. & Yamada, K., 2002. Bridge weigh-in-motion systems using stringers of plate girder bridges. In: *Third International Conference on Weigh-in-Motion (ICWIM3)*. Iowa Orlando, USA. 13-15 May 2002. p. 209-218.

Ojio, T. & Yamada, K., 2005. Bridge WIM by reaction force method. In: *Fourth International Conference on Weigh-In-Motion (ICWIM4)*. Taipei, Taiwan. 20-23 February 2005.

Ojio, T., Carey, C. H., O'Brien, E., Doherty, C. & Taylor, S. E., 2016. Contactless bridge weigh-in-motion. *Journal of Bridge Engineering*. Vol. 21:7. No. 04016032. DOI: 10.1061/(ASCE)BE.1943-5592.0000776.

Peters, R. J., 1984. AXWAY- a system to obtain vehicle axle weights. In: *Proceedings of the 12th Australian road research board conference*. Hobart, Australia. 27-31 August 1984. Vermont South, Australia: APRB Group Limited. Vol. 12:1. p. 10-18.

- Peters, R. J., 1986. CULWAY- an unmanned and undetectable highway speed vehicle weighing system. In: *Australian Road Research Board Proceedings*. Hobart, Australia. 25-29 August 1986. Vermont South, Australia: APRB Group Limited. Vol. 13:6. p. 70-83.
- Pihlajamäki, J., 2001. *Liikennesuorituksen laskeminen*. Espoo, Finland: Tiehallinto. 18 p. Tien pohja- ja päällysrakenteet tutkimusohjelma (TPPT).
- PONTEK OY, 2017. *Lillholmenin Siltapiirustukset*. Helsinki: Finnish Transport Agency. Available at: <https://vayla.fi/mt12029-lillholmenin-silta>.
- Quilligan, M., Karoumi, R. & O'Brien, E., 2002. Development and testing of a 2-dimensional multi-vehicle bridge-WIM algorithm. In: *3rd International Conference on Weigh-in-Motion (ICWIM3)*. Orlando, USA. 13-15 May 2002, p. 199-208.
- Rauhanen M., 2015. Ajoneuvoasetuksen muutos 2013. In: *Kuntatekniikan päivät*. [Presentation]. 21-22 May 2015. [Cited Jun. 2020]. Available at: https://kuntatekniikka.fi/wp-content/uploads/sites/2/2015/06/SKTY_Ajoneuvoasetukse-muutos_Rauhanen_Turku2015.pdf
- Richardson, J., Jones, S., Brown, A., O'Brien, E. & Hajializadeh, D., 2014. On the use of bridge weigh-in-motion for overweight truck enforcement. *International Journal of Heavy Vehicle Systems*. Vol. 21:2. p. 83-104. ISSN: 1744-232X.
- Salomaa, M., 2016. Liikennevirasto tarkistaa 18 uudehkoa siltaa eri puolilla Suomea – huonolle betonille ei ole vielä löytynyt selvää syytä. *Helsingin Sanomat*. 2 December. [Cited 6 Aug. 2020]. Available at: <https://www.hs.fi/kotimaa/art-2000004891850.html>.
- Sayed, S. M., Sunna, H. N. & Moore, P. R., 2020. Truck Platooning Impact on Bridge Preservation. *Journal of Performance of Constructed Facilities*. Vol. 34:3. No. 4020029. ISSN: 0887-3828.
- SFS-EN 1991-2, 2004. *Eurocode 1: Actions on structures. Part 2: Traffic loads on bridges*. Finnish Standards Association SFS. 165 p. [Cited 18 Dec. 2020].
- SFS-EN 1993-1-9, 2005. *Eurocode 3: Design of steel structures. Part 1-9: Fatigue*. Helsinki: Finnish Standards Association SFS. 37 p. [Cited 18 Dec. 2020].
- SFS-EN 1993-2, 2007. *Eurocode 3. Design of steel structures. Part 2: Steel Bridges*. Helsinki: Finnish Standards Association SFS. 103 p. [Cited 18 Dec. 2020].
- Silvester, K., Lilja, H. & Tirkkonen, T., 2020. Specialists. *Trafikia AB and Finnish Transport Infrastructure Agency*. Stockholm, Sweden, 164 40, Trafikia AB. [Interview, 30 Nov. 2020 and 14 Dec. 2020].
- Skokandić, D., Mandić-Ivanković, A. & Ivica, D., 2016. Multi-level road bridge assessment. In: Elfgrén, L.(ed.) of *19th IABSE Congress 2016: Challenges in Design and Construction of an Innovative and Sustainable Built Environment*. Stockholm, Sweden. 21-23 September 2016. Zürich, Switzerland: International Association for Bridge and Structural Engineering (IABSE). p. 970-977. ISBN: 9781510835900.

Skokandić, D., Žnidarič, A., Mandić Ivanković, A. & Kreslin, M., 2017. Application of Bridge Weigh-in-Motion measurements in assessment of existing road bridges. In: *Proceedings of JOINT COST TU1402-COST TU1406-IABSE WC1 WORKSHOP "The Value of Structural Health Monitoring for the reliable Bridge Management"*. Zagreb, Croatia. 2-3 March 2017. 8 p. DOI: <https://doi.org/10.5592/CO/BSHM2017.4.6>.

Tiehallinto, 2008. *Liikkuvan ajoneuvon painon mittaaminen, siltaan asennettavan järjestelmän (Bridge-WIM) testaus*. Helsinki, Finland. 34 p. Tiehallinnon sisäisiä julkaisuja 7/2008. ISSN: 1459-1561.

Toikka, J. & Virtala, P., 2015. *Akselimassatutkimus 2013-2014: projektin loppuraportti*. Helsinki, Finland: Liikennevirasto, tekniikka ja ympäristö -osasto. 74 p. Liikenneviraston tutkimuksia ja selvityksiä 67/2015. ISBN: 978-952-317-179-4.

Väylävirasto, 2020. *Väyläviraston sillat 1.1.2020: Sillaston rakenne, palvelutaso ja kunto - Osa 1 Tiesillat, Osa 2 Rataverkon sillat*. Available at: <http://urn.fi/URN:ISBN:978-952-317-801-4>. ISSN: 9789-523178014.

Yu, Y., Cai, C. S. & Deng, L., 2016. State-of-the-art review on bridge weigh-in-motion technology. *Advances in Structural Engineering*. Vol. 19:9. p. 1514-1530. ISSN: 1369-4332.

Zhao, H., Uddin, N., O'Brien, E., Shao, X. & Zhu, P., 2014. Identification of Vehicular Axle Weights with a Bridge Weigh-in-Motion System Considering Transverse Distribution of Wheel Loads. *Journal of Bridge Engineering*. Vol. 19:3 No. 04013008. DOI: 10.1061/(ASCE)BE.1943-5592.0000533

Žnidarič, A. & Lavrič, I., 2010. Applications of B-WIM technology to bridge assessment. In: *Fifth International Conference on Bridge Maintenance, Safety and Management, IABMAS*. Philadelphia, USA. 11-15 July 2010. DOI: 10.1201/b10430-142.

Žnidarič, A., Kreslin, M., Lavrič, I. & Kalin, J., 2012. Simplified Approach to Modelling Traffic Loads on Bridges. *Procedia - Social and Behavioral Sciences*. Vol. 48 p. 2887-2896. ISSN: 1877-0428.

Žnidarič, A. & Kalin, J., 2020. Using bridge weigh-in-motion systems to monitor single-span bridge influence lines. *Journal of civil structural health monitoring*. Vol. 10:5. p. 743-756. ISSN: 2190-5452.

Appendices

Appendices

Appendix 1 – Fatigue load model 4 calculations. 4 pages.

Appendix 2 – Traffic histograms. 11 pages

Appendix 3 – Damage figures from measurements. 3 pages

Appendix 1 Fatigue load model 4 calculations

Step 1:

Fatigue safety factor: $\gamma_{Ff} := 1$

Design life: $t_{Ld} := 100 \text{ yr}$

$i := 1 \dots 5$

$j := 1 \dots 3$

Material safety factor: $\gamma_{Mf} := 1.35$

Critical region details are at least 2 meters from the expansion seam:

$$\Delta\varphi_{fat} := \max\left(1.3 \cdot \left(1 - \frac{2 \cdot m}{26 \cdot m}\right), 1\right) = 1.2$$

Stress amplitude for three wheel types:

Fatigue class of the detail:

Number of heavy vehicles per year and per lane:

$$\Delta\sigma_{p_1} := 40.2 \text{ MPa}$$

$$\Delta\sigma_C := 71 \text{ MPa}$$

$$N_{Obs} := 0.01 \cdot 10^6$$

$$\Delta\sigma_{p_2} := 32.0 \text{ MPa}$$

$$\Delta\sigma_{p_3} := 38.9 \text{ MPa}$$

$$\Delta\sigma_{C,d} := \frac{\Delta\sigma_C}{\gamma_{Mf}} = 52.593 \text{ MPa}$$

Calculating the design detail category

$$\Delta\sigma_{D,d} := \left(\frac{2}{5}\right)^{\frac{1}{3}} \cdot \Delta\sigma_{C,d} = 38.751 \text{ MPa}$$

Calculating the constant amplitude fatigue limit

$$\Delta\sigma_{L,d} := \left(\frac{5}{100}\right)^{\frac{1}{5}} \cdot \Delta\sigma_{D,d} = 21.285 \text{ MPa}$$

Calculating the Cut-off limit

$$N_{LORRY} := \begin{bmatrix} 80\% \\ 5\% \\ 5\% \\ 5\% \\ 5\% \end{bmatrix} \cdot N_{Obs} = \begin{bmatrix} 8 \cdot 10^3 \\ 500 \\ 500 \\ 500 \\ 500 \end{bmatrix}$$

Setting the corresponding number of lorries according to the traffic type
EN 1991-2 Table 4.7

Step 2:

Stress amplitudes after dynamic amplification:

$$\Delta\sigma_p := \Delta\sigma_p \cdot \Delta\varphi_{fat} = \begin{bmatrix} 48.24 \\ 38.4 \\ 46.68 \end{bmatrix} \text{ MPa}$$

$$\frac{\Delta\sigma_p}{50} = \begin{bmatrix} 0.965 \\ 0.768 \\ 0.934 \end{bmatrix} \text{ MPa}$$

Lorries axle number and wheel types according to EN 1991-2 Table 4.7:

$$n_{axle1} := \begin{bmatrix} 1 & 1 & 0 \\ 1 & 2 & 0 \\ 1 & 1 & 3 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad n_{axle2} := \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

Equivalent axle weight factors according to EN 1991-2 Table 4.7 (Linear model is assumed):

$$k_{axle1} := \begin{bmatrix} 0.7 & 1.3 & 0 \\ 0.7 & 1.2 & 0 \\ 0.7 & 1.5 & 0.9 \\ 0.7 & 1.4 & 0 \\ 0.7 & 1.3 & 0.9 \end{bmatrix} \quad k_{axle2} := \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0.9 & 0 \\ 0 & 0 & 0.8 \end{bmatrix}$$

$$\Delta\sigma_{axle1_{i,j}} := k_{axle1_{i,j}} \cdot \Delta\sigma_{p_j}$$

$$\Delta\sigma_{axle2_{i,j}} := k_{axle2_{i,j}} \cdot \Delta\sigma_{p_j}$$

Stress amplitude of every axle/wheel combination:

$$\Delta\sigma_{axle1} = \begin{bmatrix} 33.768 & 49.92 & 0 \\ 33.768 & 46.08 & 0 \\ 33.768 & 57.6 & 42.012 \\ 33.768 & 53.76 & 0 \\ 33.768 & 49.92 & 42.012 \end{bmatrix} \text{ MPa} \quad \Delta\sigma_{axle2} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 34.56 & 0 \\ 0 & 0 & 37.344 \end{bmatrix} \text{ MPa}$$

Total number of axles in 100 years:

$$Tot_{1_{i,j}} := n_{axle1_{i,j}} \cdot N_{LORRY_i} \cdot \frac{t_{Ld}}{\text{yr}} \quad Tot_1 = \begin{bmatrix} 8 \cdot 10^5 & 8 \cdot 10^5 & 0 \\ 5 \cdot 10^4 & 1 \cdot 10^5 & 0 \\ 5 \cdot 10^4 & 5 \cdot 10^4 & 1.5 \cdot 10^5 \\ 5 \cdot 10^4 & 5 \cdot 10^4 & 0 \\ 5 \cdot 10^4 & 5 \cdot 10^4 & 5 \cdot 10^4 \end{bmatrix}$$

$$Tot_{2_{i,j}} := n_{axle2_{i,j}} \cdot N_{LORRY_i} \cdot \frac{t_{Ld}}{\text{yr}} \quad Tot_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 \cdot 10^5 & 0 \\ 0 & 0 & 1 \cdot 10^5 \end{bmatrix}$$

Step 3:

Calculating corresponding cycles to failure for every axle/wheel combination from S-N curve (EN 1993-1-9 Figure 7.1):

$$N_{R.axle1_{i,j}} := \text{if } \max(0.1 \text{ MPa}, \Delta\sigma_{axle1_{i,j}}) > \left(\frac{2}{5}\right)^{\frac{1}{3}} \cdot \Delta\sigma_{C.d}$$

$$\left\| 2 \cdot 10^6 \cdot \left(\frac{\Delta\sigma_{C.d}}{\max(0.1 \text{ MPa}, \Delta\sigma_{axle1_{i,j}})} \right)^3 \right\|$$

$$\text{else if } \max(0.1 \text{ MPa}, \Delta\sigma_{axle1_{i,j}}) > \left(\frac{5}{100}\right)^{\frac{1}{5}} \cdot \Delta\sigma_{D.d}$$

$$\left\| 5 \cdot 10^6 \cdot \left(\frac{\Delta\sigma_{D.d}}{\max(0.1 \text{ MPa}, \Delta\sigma_{axle1_{i,j}})} \right)^5 \right\|$$

else

$$\left\| 1 \cdot 10^{20} \right\|$$

Figure 7.1.

$$N_{R.axle1} = \begin{bmatrix} 9.95 \cdot 10^6 & 2.339 \cdot 10^6 & 1 \cdot 10^{20} \\ 9.95 \cdot 10^6 & 2.973 \cdot 10^6 & 1 \cdot 10^{20} \\ 9.95 \cdot 10^6 & 1.522 \cdot 10^6 & 3.924 \cdot 10^6 \\ 9.95 \cdot 10^6 & 1.873 \cdot 10^6 & 1 \cdot 10^{20} \\ 9.95 \cdot 10^6 & 2.339 \cdot 10^6 & 3.924 \cdot 10^6 \end{bmatrix}$$

$$N_{R.axle2_{i,j}} := \text{if } \max(0.1 \text{ MPa}, \Delta\sigma_{axle2_{i,j}}) > \left(\frac{2}{5}\right)^{\frac{1}{3}} \cdot \Delta\sigma_{C.d}$$

$$\left\| 2 \cdot 10^6 \cdot \left(\frac{\Delta\sigma_{C.d}}{\max(0.1 \text{ MPa}, \Delta\sigma_{axle2_{i,j}})} \right)^3 \right\|$$

$$\text{else if } \max(0.1 \text{ MPa}, \Delta\sigma_{axle2_{i,j}}) > \left(\frac{5}{100}\right)^{\frac{1}{5}} \cdot \Delta\sigma_{D.d}$$

$$\left\| 5 \cdot 10^6 \cdot \left(\frac{\Delta\sigma_{D.d}}{\max(0.1 \text{ MPa}, \Delta\sigma_{axle2_{i,j}})} \right)^5 \right\|$$

else

$$\left\| 1 \cdot 10^{20} \right\|$$

$$N_{R.axle2} = \begin{bmatrix} 1 \cdot 10^{20} & 1 \cdot 10^{20} & 1 \cdot 10^{20} \\ 1 \cdot 10^{20} & 1 \cdot 10^{20} & 1 \cdot 10^{20} \\ 1 \cdot 10^{20} & 1 \cdot 10^{20} & 1 \cdot 10^{20} \\ 1 \cdot 10^{20} & 8.861 \cdot 10^6 & 1 \cdot 10^{20} \\ 1 \cdot 10^{20} & 1 \cdot 10^{20} & 6.015 \cdot 10^6 \end{bmatrix}$$

Step 4:

Using Miner's rule to calculate total damage:

$$Di := \sum_i \sum_j \left(\frac{Tot_{1,i,j}}{\max(1, N_{R.axle1,i,j})} \right) + \sum_i \sum_j \left(\frac{Tot_{2,i,j}}{\max(1, N_{R.axle2,i,j})} \right) = 0.636$$

Calculating the damage caused by every wheel:

$$Wheel_ABC_j := \sum_i \left(\frac{Tot_{1,i,j}}{\max(1, N_{R.axle1,i,j})} \right) + \sum_i \left(\frac{Tot_{2,i,j}}{\max(1, N_{R.axle2,i,j})} \right) = \begin{bmatrix} 0.1005 \\ 0.4679 \\ 0.0676 \end{bmatrix}$$

Calculating the damage caused by every axle:

$$var1_{i,j} := \left(\frac{Tot_{1,i,j}}{\max(1, N_{R.axle1,i,j})} \right) \quad var1 = \begin{bmatrix} 0.08 & 0.342 & 0 \\ 0.005 & 0.034 & 0 \\ 0.005 & 0.033 & 0.038 \\ 0.005 & 0.027 & 0 \\ 0.005 & 0.021 & 0.013 \end{bmatrix}$$

$$var2_{i,j} := \left(\frac{Tot_{2,i,j}}{\max(1, N_{R.axle2,i,j})} \right) \quad var2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0.011 & 0 \\ 0 & 0 & 0.017 \end{bmatrix}$$

$$Single_axle := \sum_j \sum_i var1_{i,j} - var1_{2,2} - var1_{3,3} = 0.536$$

$$Dual_axle := var1_{2,2} + \sum_j \sum_i var2_{i,j} = 0.062$$

$$Triple_axle := var1_{3,3} = 0.038$$

$$Axles := \begin{bmatrix} Single_axle \\ Dual_axle \\ Triple_axle \end{bmatrix} = \begin{bmatrix} 0.5362 \\ 0.0615 \\ 0.0382 \end{bmatrix}$$

Appendix 2 Traffic histograms

Kaarina 2014 (not included in analysis):
Lane 1 (northbound)

Lane 2 (southbound)

Combined

Kaarina 2016:
Lane 1 (northbound)

Lane 2 (southbound)

Combined

Kehä III 2015:
Kehä III West

Kehä III East

Kehä III combined

Kehä III 2017:
Kehä III West

Kehä III East

Kehä III combined

Olhava 2013:
Lane 1 (northbound)

Lane 2 (southbound)

Combined

Olhava 2014 (error in measurements):
Lane 1 (northbound)

Lane 2 (southbound)

Combined

Olhava 2015:
Lane 1 (northbound)

Lane 2 (southbound)

Combined

Olhava 2016 (Construction work near the measurement site):
Lane 1 (northbound)

Lane 2 (southbound)

Combined

Olhava 2017:
Lane 1 (northbound)

Lane 2 (southbound)

Combined

Olhava 2018:
Lane 1 (northbound)

Lane 2 (southbound)

Combined

Combined traffic applied in analyses:
Kaarina 2016, local traffic:

Kaarina 2016, medium distance traffic

Kehä III 2015 & 2017, medium distance traffic:

Olhava 2015, 2017 & 2018, long distance traffic:

Appendix 3 Damage figures from measurements

Area 4:

Kaarina lane 2 – local traffic

Kaarina lane 1 & lane 2 – medium distance traffic

Kehä III – medium distance traffic

Olhava – Long distance traffic

Area 2b:
Kaarina lane 2 – local traffic

Kaarina lane 1 & lane 2 – medium distance traffic

Kehä III – medium distance traffic

Olhava – Long distance traffic

Reference detail:

Kaarina lane 2 – local traffic

Kaarina lane 1 & lane 2 – medium distance traffic

Kehä III – medium distance traffic

Olhava – Long distance traffic