Fatigue loading estimation for road bridges using long term WIM monitoring

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ABSTRACT: As bridges form the keystone of transport networks, their safe operation with minimal maintenance closures is paramount for efficient operation. Yearly increases in the volume of heavy traffic mean a higher number of fatigue damaging load cycles. The study utilises real traffic streams from Weigh-In-Motion (WIM) monitoring within the Swiss highway network performed continuously over a number of years. The concept of a Standard Fatigue Bridge Model (SFBM) is introduced which provides long term fatigue cycle data for road bridges based on the real traffic data. An algorithm was developed which simulates vehicle passages over a bridge model and calculates fatigue load effects using the axle positions recorded in real time. This information could serve as an identification tool for bridges within a stock where fatigue is likely to be a problem and could form part of a full bridge management framework.

1 INTRODUCTION

1.1 Background and motivation

Bridges are critical elements within a road network and their safe operation with minimal maintenance closures is paramount for efficient operation. Bridge managers must operate, maintain, and improve their structures whilst providing safety and comfort for the user and adhering to limited financial resources. It is estimated that there are over 930,000 road bridges in the EU-27, Norway and Switzerland combined (COST, 2002) which represents a huge economic asset to the region. Approximating financial needs for the maintenance of a stock of structures depends on the availability and quality of relevant information and data on the current condition of the structures (Brühwiler, 2008). As well as a better understanding of the structures themselves, a better knowledge of the loads acting on them is required.

Recent Swiss traffic analysis over a 5 year period between 2003 and 2007 showed that the share of total traffic volume by vehicles over 40 tonnes increased by 53% (FEDRO, 2010) while axle loads remained constant. This does not mean higher loads acting on the existing bridge stock as there are regulations on maximum Gross Vehicle Weight (GVW) in place. However, it does mean a higher number of fatigue damaging load cycles. With recent improvements in durability of materials and proactive maintenance strategies, fatigue requires increased consideration, for both steel and reinforced concrete bridges. While whole life monitoring of all bridges offers the best solution for assessment of these effects theoretically; the sheer number of bridges, manpower, energy and data storage requirements make it unsustainable at present. Approaches are also required which provide reasonably accurate information for fatigue evaluation of networks of bridges in order to identify bridges within a stock where fatigue is likely to be a problem.

Simulating the highly stochastic traffic events allowing for meetings of vehicles, overtaking, and variations in speed and traffic patterns requires substantial effort. In addition, when modelling traffic behaviour using Monte Carlo analysis real traffic trends can be lost and vehicles occurrences can be simulated which in reality cannot happen for logistical or regional reasons. With the advancements in data storage capacity and monitoring technologies in recent years, fatigue load effects could also be studied by examining real traffic streams from continuous traffic load monitoring.

1.2 Approach

This paper addresses the issue of fatigue causing load effects from everyday traffic. A method is proposed for assessment of fatigue cycles to be used in the assessment of longitudinal girders or slab elements of short to medium span road bridges (15–45 m) using real time long term traffic recordings. In this study vehicle positioning is taken directly from the (WIM) Weigh-In-Motion data as the time is known between vehicle crossings thereby removing the need for classification of vehicles. A WIM system measures the weight of a vehicle moving at speed and modern WIM installations can record the total weight, individual axle

load, wheel base, vehicle category, speed, vehicle length and time intervals for all vehicles crossings.

From a bridge fatigue effect point of view the important parameters are the frequency and magnitude of axle loads and the spacing between them in time as they cross a bridge. The information obtained from the proposed method is local to the traffic in the region of the chosen WIM station and consideration must be given to the differences in traffic makeup if being used for examination of bridges outside that region.

2 WIM DATA AND USE IN FATIGUE SAFETY ASSESSMENT

2.1 *Previous work utilising WIM data for fatigue effects*

Much of the work to date with WIM technology has focused on the modelling of the extreme load events which threaten the ultimate limit capacity of a bridge structure. Until recently the recording of long term traffic data was limited by the technologies involved and data storage issues. For this, reason random processes such as Monte Carlo simulations of short datasets or extrapolation by means of Extreme Value Theory was often performed.

Studies have shown that fatigue evaluation is highly site specific and that the actual fatigue damage resulting from the use of WIM data is often underestimated or overestimated by the code specified fatigue trucks according to Sivakumar et al., (2008). Cumulative fatigue damage from the WIM data were compared to that of the codified fatigue trucks to determine fatigue damage adjustment factors. Laman et al. (1996) presented a fatigue live load model for steel girder bridges obtained from WIM measurements which consisted of site specific truck parameters and component specific stress spectra. Jacob and Labry (2002) examined a number of short duration WIM datasets of heavy traffic in order to verify that some critical details of steel-concrete composite bridges comply with the relevant design codes. The CASTOR-LCPC software was presented which simulates traffic flow on a bridge and calculates the induced traffic load effects. Wang et al. (2005) combined truck WIM data collected to establish live load spectra to perform fatigue damage analysis for typical girder bridges. It was found that truck loading effects did not necessarily increase with GVW therefore it is closely related to the axle configuration.

2.2 *Swiss WIM systems*

In cooperation with the cantons, the Federal Roads Office (FEDRO) operates 8 WIM stations on the national road network. A permanent monitoring

system at Mattstetten on the A1 east-west motorway between Zurich and Bern with long term recording ability was chosen for this study and 3 years of continuous data (2008–2009) are examined. This station consists of a pavement embedded WIM system with a layout as illustrated in Figure 1. The sensors are of the piezo electric type incorporating a quartz disc type which emitsanelectrical charge proportional to the forces applied by vehicle tyres thereby enabling the calculation of axle loads and time between them.

The inductive loops determine the position of the front and back of the vehicle while the sensors calculate the axle loads, axle spacing's and vehicle velocity. Figure 2 shows the daily traffic flow through the WIM station in the Zurich direction during 2009.

It can be seen in Figure 3 that the overall GVW distribution in each direction show very similar trends from year to year. These distributions were generally found to exhibit 2 peaks like many previous studies including Bailey (1996). These peaks represent the occurrence of fully loaded and empty trucks.

3 WIM DATA TREATMENT

3.1 *Filtering of fatigue relevant traffic data*

The effects of standard passenger cars are not considered to cause fatigue damage to highway bridges due to their small loading relative to the design heavy vehicles (Jacob & Labry, 2002). In this study a car is defined as a vehicle of 3.5 tonnes or less and WIM results below this value are not assessed. Meystre & Hirt (2006) showed that for this particular WIM station in 2003, 86% of vehicles were light cars less than 3.5 tonnes. In many bridges, the lighter traffic in the dataset close to the 3.5 tonnes GVW may be non-damaging as regards
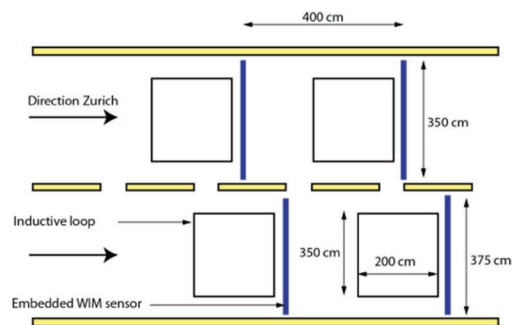

Figure 1. Pavement embedded WIM sensor layout at MattstettenA1 WIM station in the Zurich direction (Adapted from FEDRO, 2010).
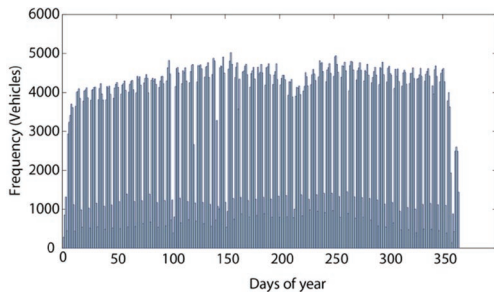
Figure 2. Daily vehicle (>3.5 tonnes GVW) flow for 2009 for MattstettenA1 WIM station in the direction of Zurich.
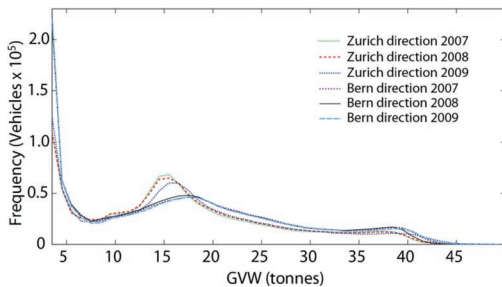

Figure 3. Mattstetten histogram of vehicles > 3.5 tonnes GVW for years 2007–2009 in both directions.

Table 1. Statistical information on traffic dataset (cleaned) used in this study for MattstettenA1 motorway WIM station.

WIM Station	2007	2008	2009
Zurich direction			
GVW > 3.5 t	1,090,330	1,103,443	1,100,071
Mean GVW (t)	17.0	17.1	17.4
Mean axle load (t)	4.63	4.62	4.71
Max GVW (t)	97.3	99.0	102
Lane 1 vehicles (%)	95.7	95.6	95.7
Lane 2 vehicles (%)	4.3	4.4	4.3
Bern direction			
GVW > 3.5 t	1,254,036	1,246,402	1,227,014
Mean GVW (t)	17.0	16.9	17.1
Mean axle load (t)	4.90	4.81	4.87
Max GVW (t)	98.8	97.9	99.0
Lane 1 vehicles (%)	88.4	87.9	87.2
Lane 2 vehicles (%)	11.6	12.1	12.8

fatigue as the stress ranges induced in the bridge elements will be below the fatigue limit of the component details.

The WIM station used is regularly calibrated and verified against the Cost 323 standard (1999). However due to the dynamic nature of moving loads, low percentages of erroneous results can arise during everyday use. Therefore some filtering of the data is required. OBrien & Enright (2011) described a series of filters for the cleaning of WIM data based on experiences with a number of European monitoring sites. It was found that the following filters were necessary for the case of the Swiss WIM data and were applied to remove erroneous results. Any vehicle incorporating one or more of the following abnormalities was removed:

– Wheelbase > vehicle length
– Overhang (Vehicle length—wheelbase) > 5.5 m
– Axle spacing > 20 m
– Axle spacing < 0.4 m
– Sum of axle loads > GVW
– Single axle load > 40 tonnes
– Single axle load > 85% total GVW

The resulting clean dataset used in this study is presented in Table 1. Further filtering methods can include observation of incorrectly split vehicles using video recordings but the purpose of this work is to demonstrate the method of fatigue cycle calculation and does not consider these.

3.2 *Traffic velocity*

Traffic flow can be viewed as free flowing by inspection of the 3 year average in Figure 4. It was not necessary to remove vehicle velocities below 60 km/h as in other studies as the WIM systems are not limited by low speed problem as encountered with some other systems. The mean velocity for all vehicles from 2007 to 2009 in all lanes is 88.3 km/h.

3.3 *Headways*

The headway is defined as the distance from the front axle of a vehicle to the front axle of the following vehicle. The data in this study was recorded with a time stamp of 0.1 seconds but the raw data was rounded to the nearest second during data storage. For the purposes of this study where zero time headways were recorded due to this rounding effect a minimum spacing of 10 m was imposed between the back axle of a vehicle to the front axle of the following vehicle. This should be conservative for free flowing traffic given the average velocities encountered in Figure 4 however it can be better examined by measuring the headway time to a greater precision in future work. This limitation has a minor affect the overall demonstration of the method as the headway distance of 1 second or less occurs for less than 4% of all vehicle crossings in the study.
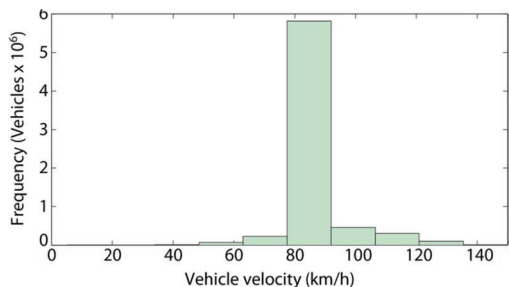
Figure 4.   Average traffic velocity for Mattstetten WIM station in both directions for years 2007, 2008 and 2009.

4   CALCULATION OF FATIGUE ACTION EFFECTS

4.1   *Concept of standard fatigue bridge model*

The Standard Fatigue Bridge Model (SFBM) is a fictitious bridge situated at the location of a long term WIM system within a road network. The vehicle arrivals at the WIM station on either side of the highway are considered to correspond to the midpan of this model bridge. Traffic passages over this bridge using real WIM data are analysed over long periods and the load effects are calculated in order to generate a signature fatigue stress cycle histogram for this point in the network. This can be used as a measure of the fatigue severity of a given location. WIM stations are required in all lanes on both sides of the road in order to be able to calculate the full effects on this fictitious model. The SFBM will be better estimated using longer measurement periods but can be presented in terms of daily cycles to compare the fatigue severity of different locations.

4.2   *Steps simulation of traffic action effects*

The vehicle headways are calculated and adjusted as described in section 3.3. An algorithm is run which calculates the bending effects in the beam as the axle loads cross over the bridge in steps of 1 m. The vehicles are simulated crossing the bridge with a constant velocity i.e. headway distance remains the same during passage. For this study the vehicles in the fast lane are merged into the slower lane and global beam effects are calculated.

4.3   *Cycle analysis and counting*

After simulation of all vehicle crossings on the bridge a rainflow cycle counting procedure is applied to calculate the number of bending moment events on the bridge model. The same procedure can be applied for shear force or any other internal force.

5   RESULTS

5.1   *Vehicle simulations on one bridge*

The results of a simulation of vehicle crossings can be outputted as bending moment or shear force cycles in the simplest form. Figure 5 illustrates the bending moment cycles resulting in a 25 m span simply supported bridge under the influence of traffic (over 1.1 million trucks) in the Zurich direction for the year 2009. It is evident that the vehicle configuration and loading variation lead to two peaks in the histogram as observed in Figure 3 for the GVW.

5.2   *Repeatability of measurements*

Figure 6 presents results of 3 years of simulations for the same beam scenario. The curves represent the histogram of bending moments over the defined periods reduced to a 1 day average value which would allow comparison of fatigue load cycle severity with other WIM stations.

5.3   *Application for design or assessment*

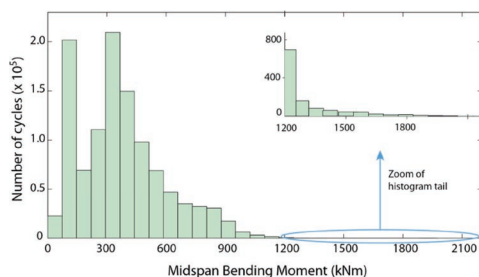The next step in usingthe previously presented methods for assessment is to determine the relevant

Figure 5. SFBM Histogram of midspanbending moment cycles for the year 2009 in Zurich direction for a simply supported 25 m span beam.
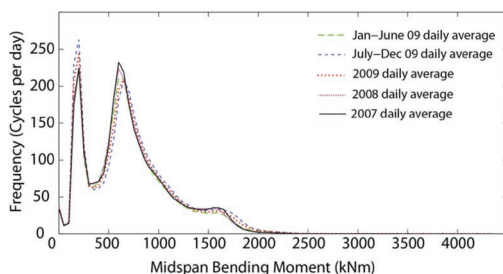

Figure 6.   Comparison of midspan bending moment cycle SFBM histograms over 3 years for a simply supported 25 m span beam using traffic in Zurich direction.

effects, e.g. fatigue stress cycles, in the bridge members from the calculated histograms.

The number of cycles to be considered could be based on the SFBM histograms with sufficient safety margins and with consideration given to any breaks in operation of the WIM system. Lateral load distribution factor for the elements under consideration can be obtained from structural analysis or monitoring. The dynamic amplification of static loads on a bridge structure has been presented in numerous studies including Znidaric et al. (2008) where a Bridge Weigh-In-Motion (B-WIM) system was used to measure in real-time the individual dynamic amplification of all traffic loading events on the bridge.

Damage accumulation laws such as Miner's rule or more advanced fracture mechanics approaches can then be used to estimate the remaining life of an element based using the SFBM simulation results.

6 FUTURE WORK

Further study is required to assess the repeatability of measurement and variability in final bending moment histograms away from the point of the WIM station. Use of Monte Carlo simulation such of the real vehicles and headways could be carried out as a comparison between the results observed in this paper. There has been a number of recent studies including Enright (2010) Getachew (2003) and using these techniques for extreme load events but they are adaptable for fatigue also.

A more detailed study on vehicle headway times with more precise time stamp would be beneficial in order to study capture multiple vehicle events in opposite directions.

A comparison study of the effects caused by current code fatigue truck models would be advantageous in order to see if a given area is less or more severely solicited to fatigue damage than designed for.

7 CONCLUSIONS

This paper demonstrated that recent improvements in data storage and WIM technologies give the potential for wider application in the domain of bridge fatigue safety examination. This ability to deal with huge datasets was impossible a short time ago and should be exploited.

The obtained fatigue cycle information is local to the area of the WIM station and should be only used to assess bridges within that network of the same traffic volume. Comparison of the SFBM results from several sites within a network could lead to more general approaches allowing for adjustment of results based on traffic volumes.

Such techniques allow a more refined and realistic consideration of fatigue damaging traffic effects for a particular area. Use of local 'on line' up to date information instead of general conservative codes which are adaptable for wide regions can aid in maximising the fatigue life of bridge structures, minimising unnecessary interventions and predicting future fatigue problems.

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