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Testing of Bridge Weigh-In-Motion System in Sub-Arctic Climate

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ABSTRACT: Systems for weighing vehicles while they are in motion are in widespread use in many countries. The accuracy of these weigh-in-motion (WIM) systems is strongly influenced by the road profile and vehicle dynamics. Systems based on sensors that are embedded in the pavement or placed on top of the road surface can only measure the axle load for the fraction of a second for which the wheels are present on the sensor. An alternative to pavement WIM systems that increases the length of the load-sensitive element is to use an existing bridge as a weighing scales (Bridge WIM). A major test of a Bridge WIM system at a test site near the Arctic Circle is described in this paper.

The test was conducted alongside a larger test of pavement WIM systems. A large number of trucks from random traffic were weighed statically and the results compared to those from the Bridge WIM system. The accuracy of the system is assessed in accordance with the COST 323 WIM specification which provides a standardized method of accuracy classification. The Bridge WIM system is proven to perform satisfactorily and consistently for a wide range of temperatures in near-Arctic climatic conditions.

KEYWORDS: bridges, roads and highways, site investigation, weigh-in-motion, data collection.

Introduction

Weigh-in-motion (WIM) is a method of weighing trucks and their axles while the vehicle is travelling at full highway speed. Piezoceramic strips, capacitive strips and mats, bending plates, and instrumented bridges are just some of the techniques used to determine axle weights in the time it takes for them to pass over the sensor. Many weigh-in-motion sensors still give quite an inaccurate estimate of static weights on medium or rough pavements due in considerable part to the dynamic motion of trucks and axles.

The example of test results illustrated in Fig. 1 shows a substantial scatter in measured gross weights relative to the corresponding static values.

Fig1_WIMaccuracy.xls

FIG. 1 – *Example of accuracy (gross vehicle weights) from an embedded strip sensor WIM system on a rough pavement [1].*

These data were collected at a WIM site where the pavement was rough (International Roughness Index of over 3.7). More accurate results may be achieved by using one of the following:

- a very smooth road surface in the approach (eg., concrete pavement ground to smooth finish) with advanced accurate or large base sensors [2],
- multiple sensor systems [3-6], or perhaps
- more sophisticated bridge WIM systems currently under development.

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In addition to accuracy, considerable difficulty has been experienced by some roads authorities with respect to durability, particularly in regions where deicing salts and/or studded tires are used.

Despite these difficulties, there is considerable interest in WIM throughout Europe where there are in excess of 250 WIM systems [*7*]. The reasons are the many applications for which WIM data can be used. These are discussed in detail by de Henau [*8*] but can be summarized as:

- Economical and geographical studies of freight movement
- Pavement aggressiveness and fatigue studies
- Bridge assessment and code calibration
- Enforcement of legal weight limits

Weigh-In-Motion Specification

A European WIM specification [*9*], prepared by the COST323 management [*7*], was used to assess the accuracy of the B-WIM system. This specification defines six accuracy classes, A(5), B+(7), B(10), C(15), D(25) and E. To be in a given class, there must be an acceptable statistical confidence that WIM weights will be within a specified percentage of the reference (usually static) values [*10, 11*]. The numbers in brackets indicate the confidence interval width for gross vehicle weight but there are also specified interval widths for the weights of groups of axles (tandems and tridems), individual axles and axles of a group. To comply with a given accuracy class, the calculated probability that results are within the interval $[W^s(1-\delta), W^s(1+\delta)]$ must exceed a specified minimum, π_0, where W^s is the reference (static) weight and δ is the confidence interval width. The minimum probability is a function of the sample size and the test conditions (e.g.: repeated runs of same truck or trucks taken at random from traffic stream).

Bridge Weigh-In-Motion

As an alternative to pavement WIM systems, Moses and others [*12*] developed the concept of using bridges as scales to weigh trucks in motion. In Australia a similar system appeared a few years later but was soon replaced by another that uses culverts [*13*]. There are currently around 150 such systems in operation. In the nineties, new Bridge WIM (B-WIM) systems were developed independently in Ireland [*14*] and in Slovenia [*15*].

Despite many advantages, B-WIM systems have not been widely used and are at present known only in a few countries around the world. Following the experience and results from the COST 323 action “Weigh-in-Motion of Road Vehicles” and research done in the EC 4th Framework project “WAVE – Weighing-in-motion of Axles and Vehicles for Europe”, this may change in the future.

Regardless of the system used, all B-WIM systems deal with an *existing instrumented bridge or culvert from the road network*. Main members of the structure are instrumented and strains are measured to provide information about its behavior under the moving vehicle. Most of the existing systems require axle or vehicle detectors on the pavement close to the bridge to provide vehicle type, velocity, and axle spacings. Strains are recorded during the whole vehicle pass over the structure and such redundant data provides useful information when the influence of dynamic effects due to vehicle-bridge interaction has to be accounted for. This is an advantage over pavement WIM systems where measurements of an axle last only a few milliseconds.

Measurements

The bridge selected for this test of B-WIM is shown in Fig. 2 and it is located in Alean, Sweden. The town of Lulea is situated some 160 km south of the Arctic Circle and the site for the Cold Environmental Test (CET) [*16*], Alean, is 20 km south of Lulea.

Fig2_bridge.tif

FIG. 2 – *General overview.*

The bridge is a two-span integral structure which is straight in plan and consists of two equal spans of 15 m as illustrated in Fig. 3.

Fig3_elevation.doc

FIG. 3 – *Elevation (dimensions in m).*

The bridge deck is of variable depth with a minimum depth at the center of 550 mm. It is solid in cross-section. Traffic is carried by one lane in each direction with no central median.

Eight mechanical strain amplifiers were bolted to the center of the soffit under the southbound carriageway of the first (North) span. Pneumatic tubes were fixed across the southbound lane, one before the bridge and the second immediately at the end of the first span with a recorded distance between them (Fig. 4). These tubes were fixed only at the edges of the road (for safety reasons), thereby permitting some movement of the tubes between the clamps. Pairs of tubes were joined using a connector at the center of the road.

Fig4_tubes.tif

FIG. 4 – *Layout of tubes.*

The traffic density at the site is 350 heavy vehicles per day in each direction. The speed limit for heavy vehicles is 80 km/h. A road weather information system (RWIS) for the automatic collection of weather data was installed at the test site. Fig. 5 shows the great variations in air temperature.

Fig5_temperature.xls

FIG. 5 – *Temperature variations between day and night at the test site [16].*

Testing was carried out in June 1997 (1st Summer), March 1998 (Winter) and June 1998 (2nd Summer). In all three cases, the system was reinstalled just prior to the tests. Data from strain transducers were recorded and stored as the post-weighed trucks passed over the bridge. The resulting raw data were subsequently analyzed using the Bridge WIM algorithms developed in Ireland and Slovenia [*17*], both of which are based on the work of Moses [*12*].

Repeated runs of two calibration trucks provided by the Swedish National Roads Administration were used to calibrate the system for each of the tests. Once checks were carried out, there was no further adjustment of the mechanical strain amplifiers for the remaining period of the tests. Traffic control was not used during these passes. Due to the low volume of traffic on the road, the truck was the only vehicle present on the bridge for most passes. Any of the truck passes that were affected by other vehicles being present on the bridge were not used for calibration.

A 4 Hz analog filter was utilized in the data acquisition for the 1st Summer and the Winter tests. It was found that this resulted in a loss of definition in the bridge response and therefore, virtually unfiltered data were used for the 2nd Summer test.

Post-Processing of Bridge WIM System Data

Some strain sensors were significantly more sensitive to the effects of individual axles than others. Therefore, for the 1st Summer test, the results of only one strain sensor were used for all the analyses. For the Winter test, six of eight strain sensors gave good distinct responses to individual axles and were used. For the 2nd Summer test, all eight strain sensors were used.

Moses' algorithm uses an influence line to generate an 'influence response' due to the truck, which is compared with the recorded strain. To achieve good accuracy from the Bridge WIM algorithm, it is imperative for the influence line to be as close as possible to reality. In this work, influence lines were determined experimentally, i.e., the influence line was adjusted manually until a good match was achieved between measured and calculated responses to the calibration trucks.

In early study of the data, theoretical influence lines were found to give good results at 50 km/h for the 1st summer test. However, it became apparent that the influence response was sensitive to truck speed, as can be seen from Fig. 6(*a*). It is evident in this figure that the peaks of strain from the axles at the midpoint of the bridge are lower for the 80 km/h truck and less well defined than for the 50 km/h truck. For example the steering axle has a noticeable effect at 50 km/h but is less obvious at 80km/h. The 80 km/h curve is also noticeably 'broader' than the 50 km/h one.

Effects of Filtering

The link between influence response and speed is associated with the fact that the data in the 1st Summer and Winter tests were filtered at 4 Hz by an analog filter in the data acquisition system. Fig. 6(*b*) shows typical influence responses at different speeds using unfiltered data from the 2nd Summer test. As can be seen, speed has little or no influence on these unfiltered data.

Fig6a_expdata.xls

(a)

Fig6b_expdata.xls

(b)

FIG. 6 – *Comparison of the same truck at different Speeds; (a) under a 4 Hz filter, (b) without a filter.*

Digital filtering of (unfiltered) 2nd Summer test data has shown the considerable effect that filtering can have on the quality of recordings. Samples of unfiltered data were transformed into the frequency domain in order to assess the dominant frequencies. The major frequency components will be between 0 and 4 Hz but a significant portion of the signal is at frequencies in excess of 4 Hz. It can therefore be expected that a 4 Hz filter will adversely affect the accuracy of the signal.

An (unfiltered) signal from the 2nd Summer test was filtered with a digital (Butterworth) filter in Matlab in the 4 – 7 Hz transition band, and the filtered signals produced by the filter are graphed with the unfiltered signal in Fig. 7.

Fig7_filter.xls

FIG. 7 – *Comparison of filtered and unfiltered data for filter within 4-7 Hz transition band.*

It can be clearly seen that the filter causes a major loss of definition in the peaks. The relative heights of the peaks are also much lower when filtered. This shows that filtering at 4 Hz, as was done in the 1st Summer and Winter tests, causes a reduction in the quality of the recorded data and would also cause a reduction in the accuracy of calculated gross vehicle and particularly the axle weights.

Calibration

This section presents the recommendations for finding a good experimental influence line for use with Moses' algorithm. To illustrate the best method for finding the influence line, this description will involve the method used to find the influence line for the 2nd summer test.

i) Set up Excel tables and graph.

Set up the initial graph shown in Fig. 8*(a)*. where it can be seen that the match between experiment and theory is quite poor. The Excel program has been used to generate this graph from tables of real recorded responses, and a completely theoretical influence response. The influence line is the correct size and the other lines are scaled to look smaller.

ii) Adjusting the negative part of the influence line

The first adjustment to the influence line is to multiply all the negative values, that is those past the 15 m mark, by a calibration factor. Change the calibration factor until there is a match between the negative portion of the influence response and the negative portion of the calibration trucks.

iii) Adjusting the positive part of the influence line

The next step is to adjust the values in the positive part of the influence line. This is done on a point by point basis in Excel. It is possible to change the value of a particular point by hand in the vertical direction. By clicking on a point of the influence line it is possible to adjust it and thus the influence response so that there is a better match between them. For a six-axle truck there are six points on the influence response that are affected by a change in one point on the influence line as shown in Fig. 8*(b)*.

Fig8a_InfluenceLine.xls

(a)

Fig8b_InfluenceLine.xls

(b)

FIG. 8 – *Determination of the influence line; (a) first estimate, (b) one point affecting six other points.*

To start with, the points at the start of the influence line should be adjusted as for 4.2 m of the influence response there is only one axle on the bridge, as the distance between the first axle and the second is 4.2 m in this case. Hence, all these points should be adjusted first. This method is continued point by point until a good match has been made between the influence response and the calibration truck recordings. When there is a good graphical correlation between the influence response and the recordings, it is possible to test impartially the accuracy of the adjusted influence line. Simply graph a three-axle truck or another six-axle truck, as both were used as calibration trucks, and graph the influence response for this truck and see if there is a match. The graph showing the final influence line and match is illustrated in Fig. 9.

Fig9_InfluenceLine.xls

FIG. 9 – *Final influence line*.

Perhaps the most difficult part of the point-by-point process is the last third of the first half of the influence line. Most care needs to be taken here. However the fact that any change that is made affects six other points helps greatly in making sure that the correct adjustments are made. When a point is changed then and the change is incorrect, it is immediately visible as can be seen in Fig. 8(b). As can be seen from Fig. 9 above, the agreement between the influence responses and the influence line is very close. This influence line is now ready to be used in an analysis.

There were two types of calibration truck used for the Winter and 2nd Summer tests with three different weights for each of the two truck types, so an influence line and its response could be checked graphically many times. Experimental influence lines were used to analyze all the random traffic and fast calibration trucks in the 1st Summer test. For the Winter test new experimental influence lines for the different behavior of the bridge in subarctic Winter conditions were obtained (the evidence suggested that the frozen soil resulted in greater stiffness at the bases of the abutments and piers). The two influence lines were both obtained using the method (outlined above) that was used to obtain the 80 km/h influence line for the 1st Summer test.

Bridge WIM Test Results

Results from the Bridge WIM algorithm for the 1st Summer test were analyzed in accordance with the COST 323 specification. For the gross vehicle weights, there was a 96.6% probability that results were within 10% of the static values, which exceeded the specified minimum for this sample size and test conditions of 92.8%. This means that gross weights were in accuracy class B(10) (Table 1). Similarly axle group data achieved class B(10). However, the probability of the single axle data being within the confidence interval of 15% corresponding to B(10) was only 89.3% and is less than the specified minimum of 93.5%. Thus single axle data only achieved accuracy class C(15).

TABLE 1 – Accuracy classification for 1st Summer test.

SYSTEM *Entity*	Number	Mean (%)	Std dev. (%)	π_0 (%)	Class	δ (%)	δ_{min} (%)	π (%)	Accepted class
single axle	156	-0.25	8.43	93.5	C(15)	20	17.0	97.2	C(15)
group of axles	162	2.09	5.93	93.5	B(10)	13	12.6	94.4	
gross weight	95	1.49	4.01	92.8	B(10)	10	8.6	96.6	

For the Winter test, the accuracy classification in accordance with the COST323 specification gave an accuracy class of D+(20), as the probabilities that the errors were within the confidence intervals were inside the required levels.

TABLE 2 – Accuracy classification for Winter test.

SYSTEM *Entity*	Number	Mean (%)	Std dev. (%)	π_0 (%)	Class	δ (%)	δ_{min} (%)	π (%)	Accepted class
single axle	188	-0.75	8.56	93.7	C(15)	20	17.3	97.0	D+(20)
group of axles	244	-1.31	10.06	93.9	D+(20)	23	20.4	96.7	
gross weight	126	-1.29	7.09	93.2	C(15)	15	14.5	94.1	

Results from the 2nd Summer test are presented in Fig. 10. This time, without filtering, an accuracy class of B(10) was returned (Table 3).

Fig10a_BWIMaccuracy.xls

(a)

Fig10b_BWIMaccuracy.xls

(b)

Fig10c_BWIMaccuracy.xls

(c)

FIG. 10 – *Graphs of WIM versus static weights for the 2nd Summer test; (a) gross vehicle weights, (b) axle groups, and (c) single axles.*

TABLE 3 – Accuracy classification for 2nd Summer test.

SYSTEM *Entity*	Number	Mean (%)	Std dev. (%)	π_0 (%)	Class	δ (%)	δ_{min} (%)	π (%)	Accepted class
single axle	188	-1.31	7.27	93.7	B(10)	15	14.8	94.0	B(10)
group of axles	239	-0.18	5.26	93.9	B(10)	13	10.6	98.0	
gross weight	122	-0.88	3.72	93.1	B(10)	10	7.7	98.4	

Conclusions

A Bridge WIM system was tested in sub-Arctic climatic conditions. It was shown to perform satisfactorily and consistently in a wide range of temperatures. However, it was found that the bridge response was different in Winter, possibly due to frozen supports, and that the influence line was quite different.

It was shown that filtering had an adverse influence on the clarity of the measured responses. However, despite this, reasonably accuracy was achieved for two tests in which an analog filter was used. Improved accuracy, comparable to the best WIM systems on the market today, was achieved in a final test in which unfiltered data were used.

Acknowledgement

The writers are grateful to Declan Feerick and John McNulty for their work in the analysis of the data. This research has received financial support from the Transport Directorate, DG VII, of the European Commission under the "WAVE" project. WAVE (Weigh-in-motion of Axles and Vehicles for Europe) is a transport research project in the 4th Framework programme.

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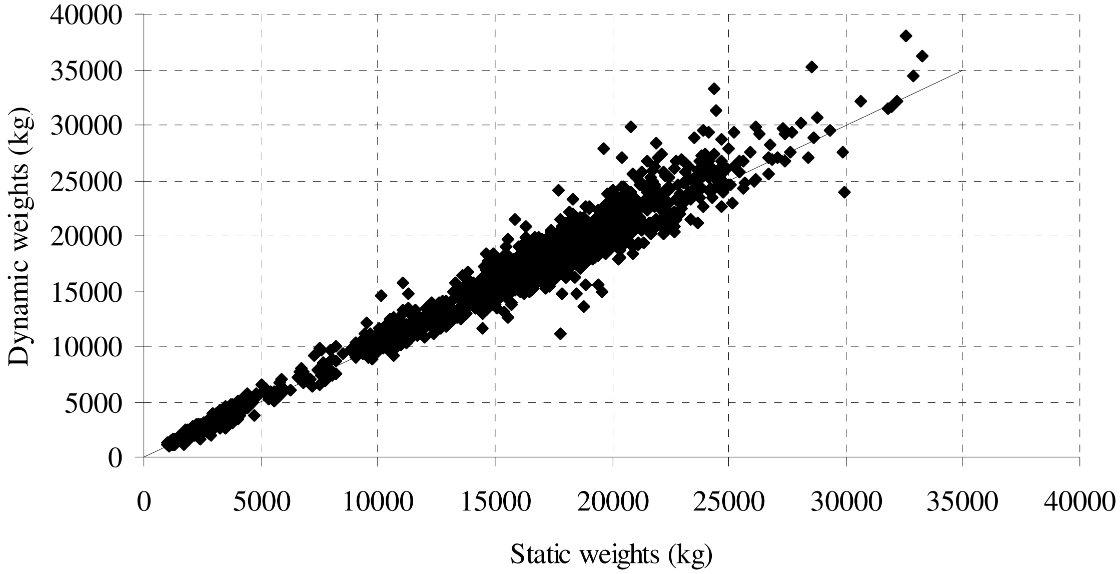

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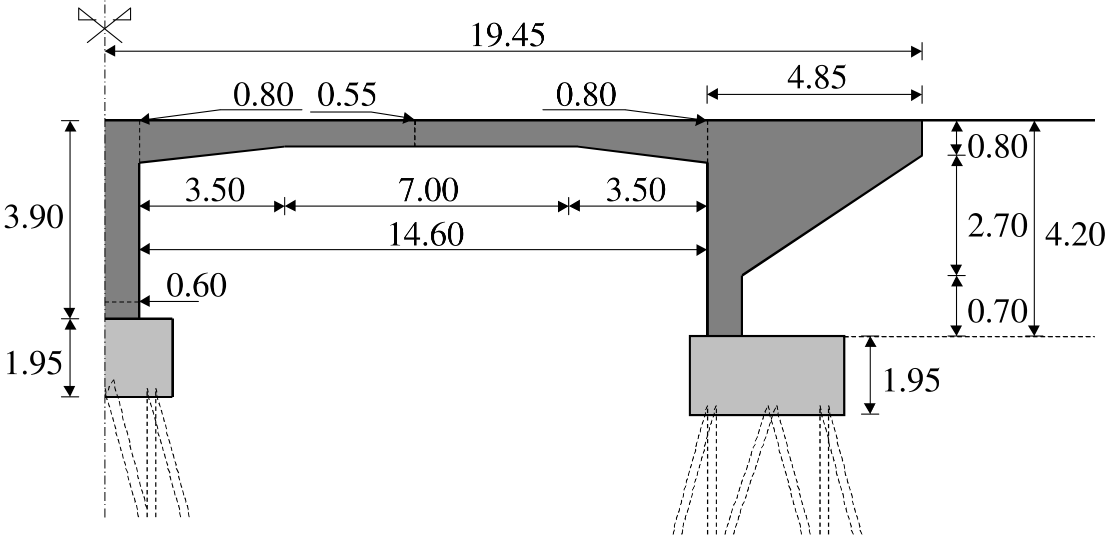
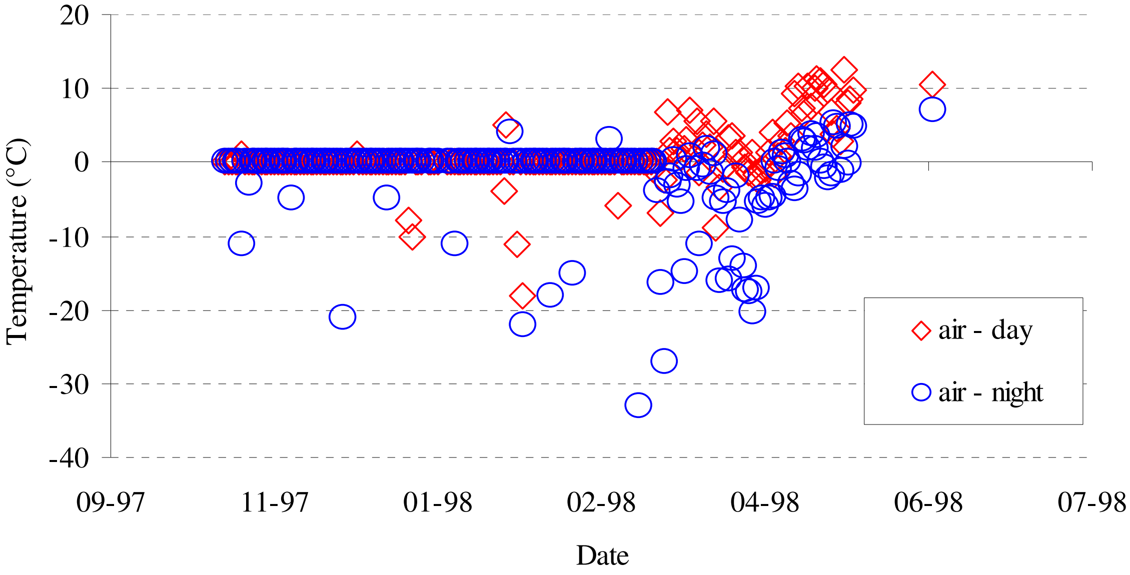


FIG. 3 – *Elevation (dimensions in m).*

FIG. 4 – *Layout of tubes.*



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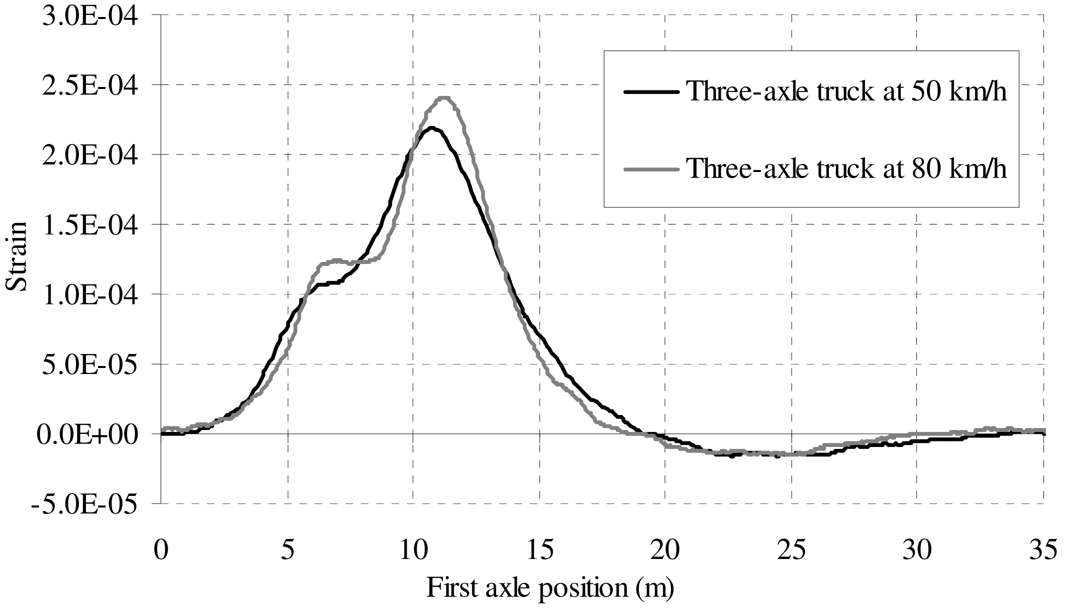

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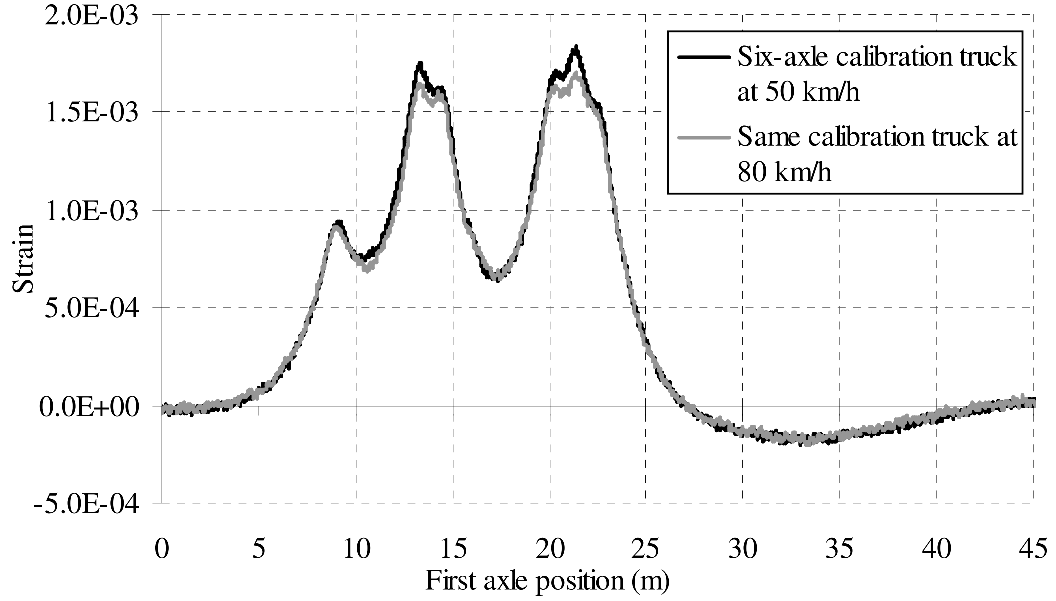

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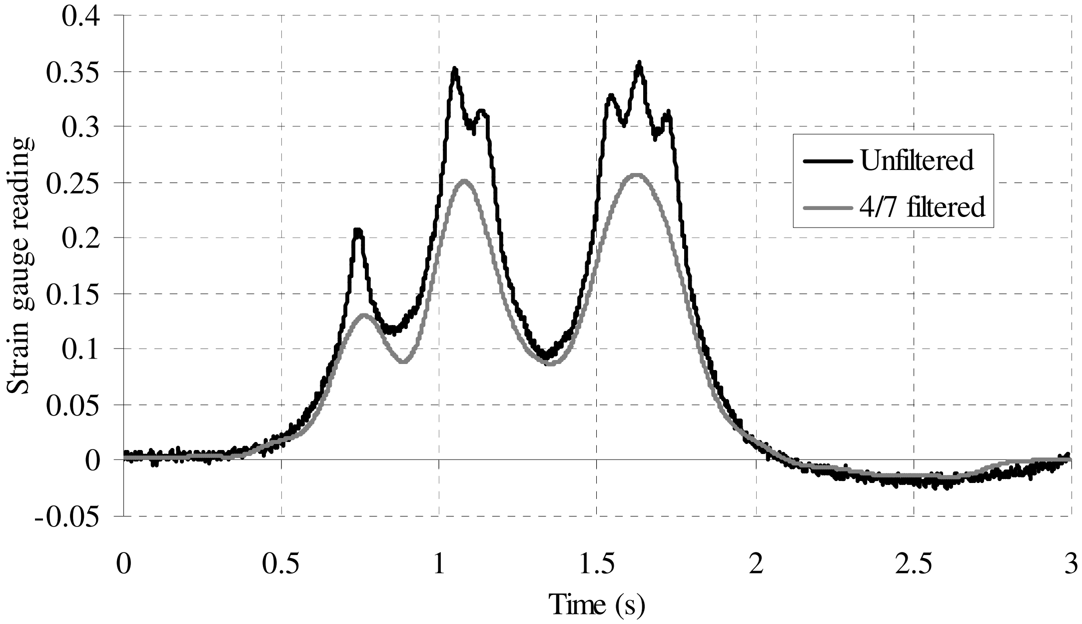

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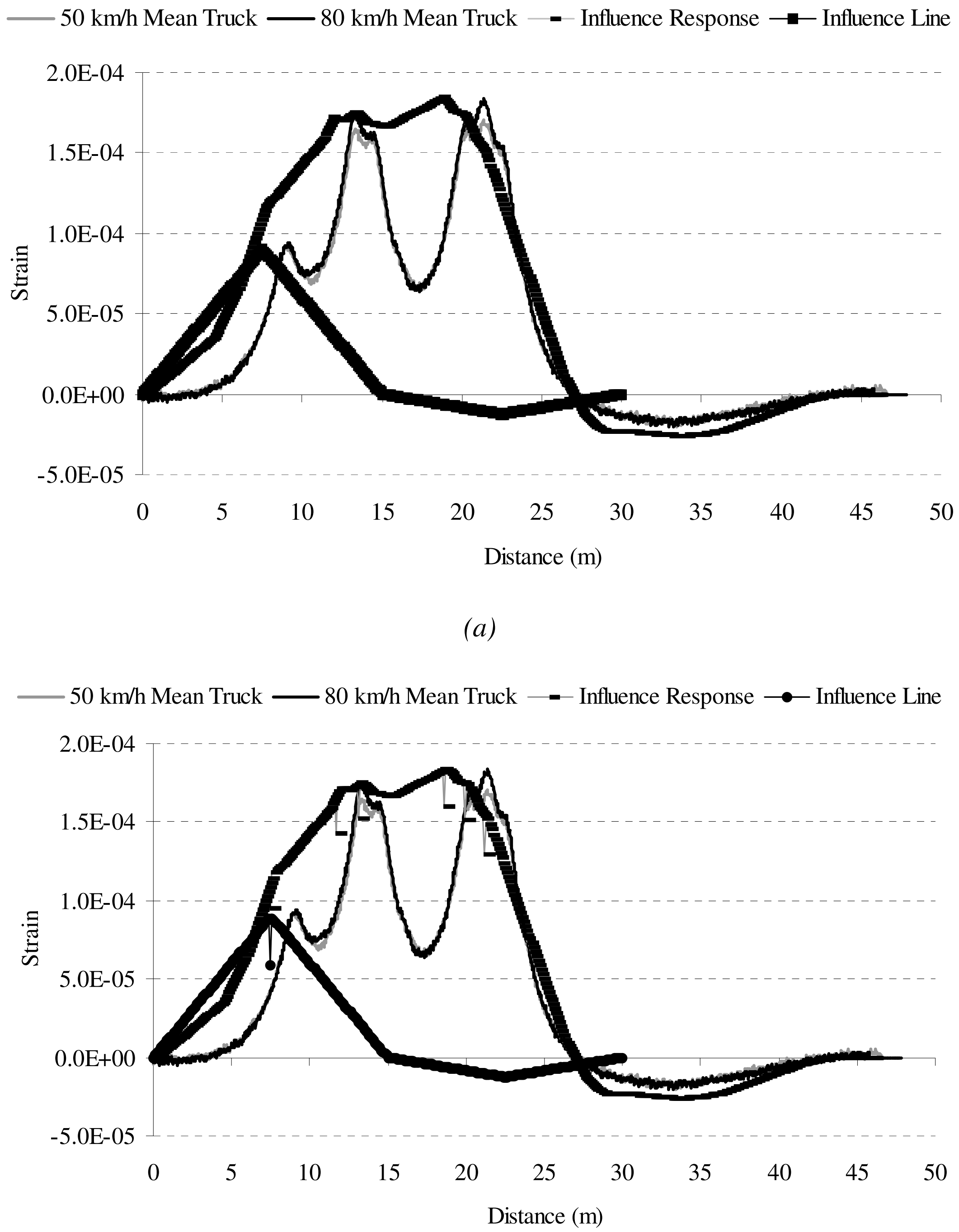

(a)

(b)

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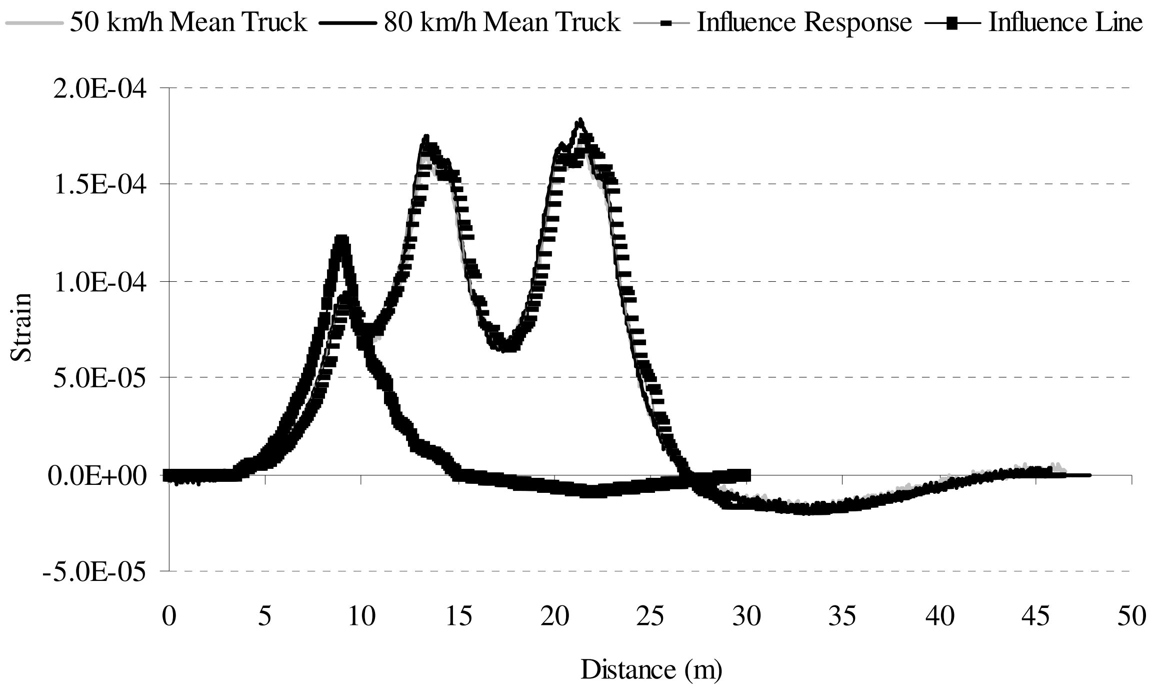

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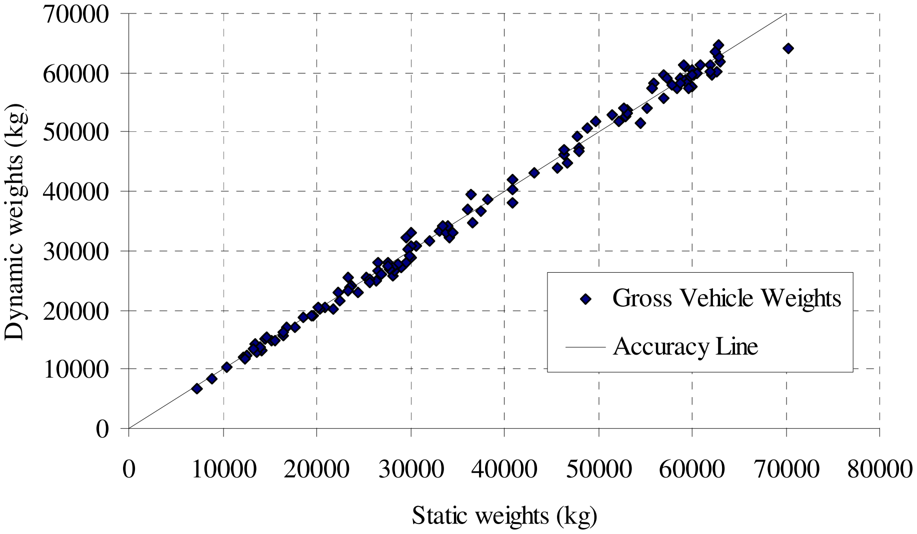
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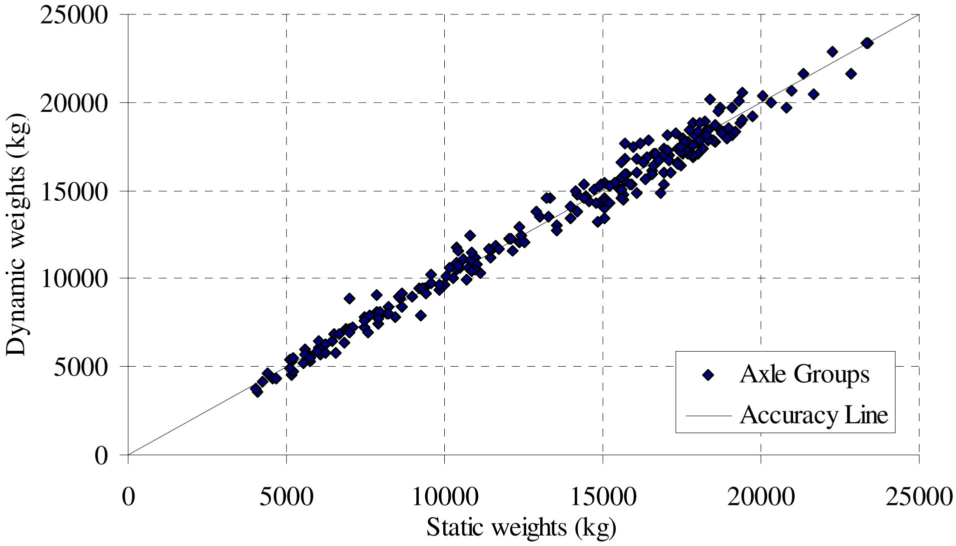
Static weights (kg)
Gross Vehicle Weights
Accuracy Line

(a)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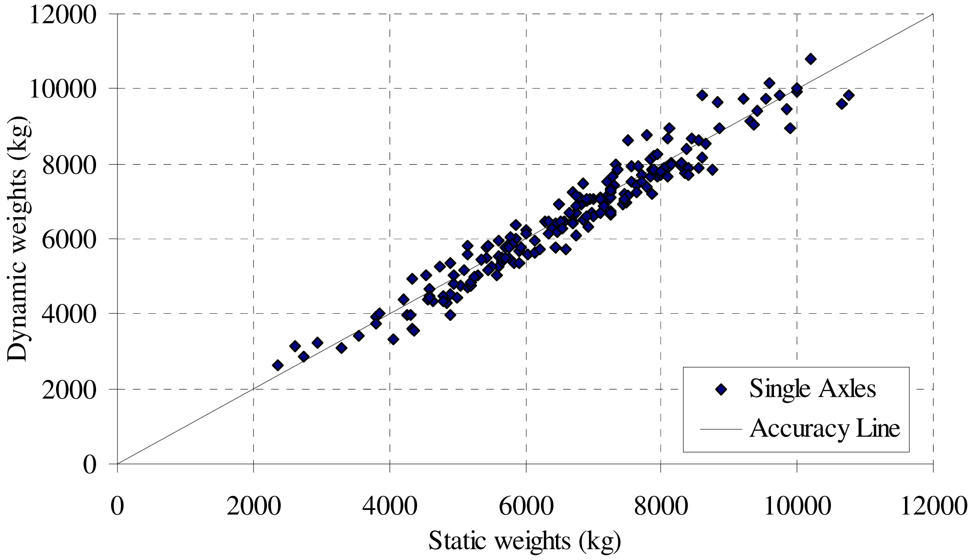
Axle Groups
Accuracy Line

(b)



(c)

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