

MEASUREMENT OF THE MAXIMUM FORCE EXERTED BY THE VEHICLE WHEELS ON THE ROAD PAVEMENT

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Abstract – Maximum value of the heavy goods vehicles axle load is the main factor accelerating the pavement damaging process. We propose two algorithms for maximum load estimation on the basis of weighing results obtained in Weigh – in – Motion systems (WIM systems). The simulation (Adams/Car) and experimental test results from an instrumented vehicle have been presented. The difficulty of the maximum load estimation consists in the fact that WIM system provide only several samples of the axle load.

Keywords: weigh in motion systems, dynamic weighing, maximum value of axle load

1. INTRODUCTION

Overloaded heavy goods vehicles pose a particular hazard for road traffic safety. Experts unanimously agree that such vehicles are the main factor worsening the condition of roads and bridges [1], [2].

Two components can be distinguished in a moving vehicle wheel load on the pavement: the static and the dynamic one. The first is caused by gravitation and can be determined for a stationary vehicle (all regulations concerning permissible loads refer to this component). The dynamic component of axle load, occurs when a vehicle is in motion. It's depends on the road quality, vehicle speed and the condition of its suspension, and in extreme cases it can attain even 40% of the static axle load. Maximum value of this component is one of the main factors that accelerate the pavement damaging process [3]. The frequency structure of such signal comprises two dominant frequencies: the first is associated with the vehicle body mass (the so-called sprung mass) and is contained within the interval 1–4 Hz, the second one is associated with the suspension and wheels mass (the so-called unsprung mass) and is contained within the range of 8–12 Hz. Fig.1 presents a signal of an instantaneous wheel load of a heavy goods vehicle and its spectrum (courtesy of the Dutch Ministry of Transport).

One of the tools used for detection of overloaded vehicles and measuring their gross weight and axle load are weigh-in-motion (WIM) systems [3], [4]. A WIM system consists of a set of load sensors built into pavement (usually 2 load sensors, but the Multi Sensors WIMs contain even several sensors), a signal conditioning system co-operating with sensors, and a master system with implemented algorithms.

The process of dynamic weighing consists in recording and processing signals generated in sensors under the

influence of the axle loads of a moving vehicle. Since the sensors are embedded in pavement perpendicularly to the direction of motion, each axle of a vehicle passing over the WIM site is weighed.

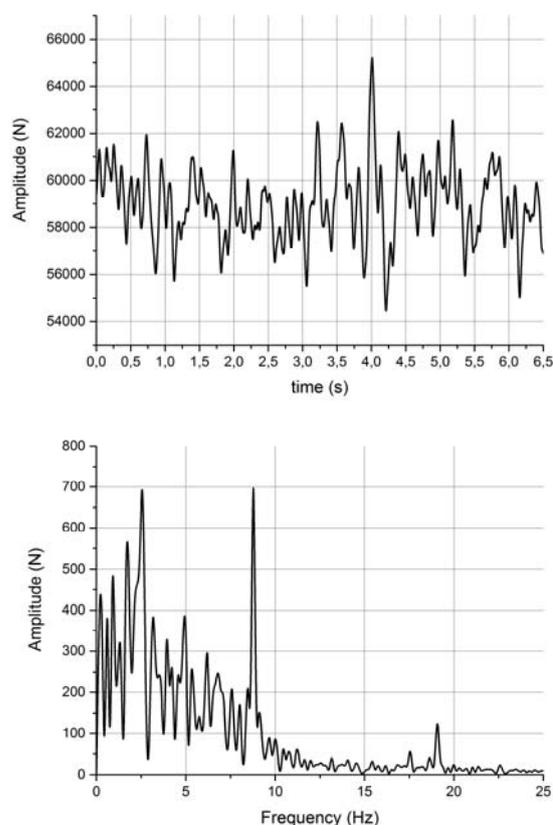


Fig. 1. The signal and its spectrum (after removing constant component) of an instantaneous wheel load of a goods vehicle at the speed of 80 km/h

The objective of measurement is the quantitative determination of two parameters that characterize the mechanical influence of a vehicle on the pavement:

- the vehicle individual static axle loads and its gross weight,
- instantaneous axle load exerted on the pavement.

Since maximum value of the axle load is the main factor that accelerates the pavement damaging process, the following question is justified:

Is it possible to reliably estimate maximum value of vehicle's axle load based on the measurements of the instantaneous axle load obtained from WIM system?

In this paper we are trying to answer this question. To the best of our knowledge, until now no research has been carried out in this area. Attempts of the maximum load estimation were solely based on axle load signals recorded from instrumented vehicles provided with the self-weighing function. Such vehicles are, however, very expensive and not easily accessible.

2. METHODOLOGY

The aim of this research was the accuracy analysis of two algorithms for determining signal maximum value (MV algorithms). The input signal for MV algorithm is a set samples of instantaneous axle load, collected in Multi Sensor WIM system. As the algorithm output result the user obtains an estimate of axle load maximum value (EMV). Accuracy analysis of such estimation process requires reference value understood as a real maximum value (RMV) of axle load. RMV may only be acquired from an instrumented vehicle which, due to measuring systems installed on the axles, is able to continuously measure its own axle load.

In our research we used signals recorded in instrumented vehicle built by Kalibra International BV [5]. Vehicle construction was as follows: the load sensors (strain gauges) were mounted on the measurement axle between the spring centre and the wheel nave. These sensors measured the force of the trailer on the axle. Measurement was compensated for the movement of the axles by measuring the vertical acceleration of the wheels and multiply it by the mass of the wheels. Vehicle is presented at Fig. 2.



Fig. 2. Instrumented vehicle

Results from instrumented vehicle are presented in part 4 of this paper but because they are limited to 8 passes with constant speed, first we decided to perform simulations in

Adams/Car software environment [6]. Such approach has at least three advantages compare to the measurements on the road:

- it allows to simulate a vehicle dynamic behaviour under various road conditions,
- performing the same tests as they normally run on a road, but in a fraction of time (and costs),
- displacements, velocities, and other quantities, especially forces applied to the road by individual wheel of a vehicle may be easily measured in such virtual model.

Adams is the world's most famous and widely used Multibody Dynamic (MBD) software, developed by MSC Software. With Adams/Car the user can quickly build complex vehicles models and conduct series of simulations.

A drawback of simulation investigation is the limited credibility of results correlated with quality of the used models. Simulations performed in the Adams/Car MSC Software environment minimize this risk factor since Adams Software is a reliable, and repeatedly verified by vehicles' manufacturers, software for vehicles' dynamics simulation. What is significant, is that Adams Software enables simulation of complex interactions between the vehicle and road. This software also allows creating models of roads in diverse classes, provided in the standard [7]. In this document road profile is described by the power spectral density (PSD) of its vertical displacement. Depending on the PSD value, a road may be classified into one of eight classes (A–H), where class A is a road of very good quality and class H means the poorest quality road. This statistical road profile description can be used for numerical calculations and was adopted for our simulations.

The objective of this simulation was to determine properties the axle load MV algorithms, more specifically the dependence of the bias error and random variability of estimators, on the number of load sensors installed on a WIM site, the vehicle's speed and pavement quality. The research consisted in simulation of a vehicle model passing over the model of a road in given class (A, B or C) with the length of 250 m. For each road class were performed passes of the virtual vehicle model at speeds of 40, 50, 60, 72, 80 and 90 km/h. The simulation results were signals of the modelled vehicle's each wheel load on pavement acquired with the spatial discretization step equal 0.1 m. The maximum value determined for these signals was taken as the reference value of maximum load generated by a given axle (RMV).

Then, for each simulation (road class/vehicle speed), the position of the weighing site was randomized with uniform distribution. The simulations also enabled the choice of the number of sensors of the virtual WIM system. The acquired set of load samples was used for determining the estimate of maximum axle load by means of MV algorithms. For each simulation 100 values of a given estimator were obtained due to randomisation of the WIM site position.

The set of estimators' values was the basis for evaluation of their statistical properties, i.e. bias error and standard

deviation, referred to the formerly determined reference value of the maximum axle load (RMV).

3. SIMULATIONS TESTS RESULTS

Two MV algorithms were adopted for the purpose of the maximum load estimation. The first algorithm takes the maximum load value recorded by any of the MS-WIM site sensors as the maximum load estimate (1).

$$Load_{max\ 1} = \max_i(\{n_i\}) \quad (1)$$

where:

n_i - the result of weighing on the WIM system i -th sensor.

It can be intuitively expected that results obtained on the basis of this estimator will be erroneous in the case of MS-WIMs equipped with a small number of sensors.

The second estimator has the form (2).

$$Load_{max\ 2} = \text{mean}_i(\{n_i\}) + 3 \cdot \text{std}_i(\{n_i\}) \quad (2)$$

where:

$\text{mean}(\)$ and $\text{std}(\)$ - denote the mean value and standard deviation, respectively.

The advantage of both estimators is that they utilize measurement results acquired solely from the WIM site, without any additional information about e.g. the vehicle class or its speed. Whereas the form of the first estimator is obvious, the second estimator is a consequence of the assumption that load samples are normally distributed.

The influence of the sensors number on the MV estimation accuracy is depicted in Fig. 3. The vehicle was travelling on a road of class B at the speed of 72 km/h.

As expected, increasing the number of sensors increases the maximum load estimate accuracy, as shown in Fig. 3. Both the bias error and standard deviation of estimators were reduced. On the road of class B the relative bias error for estimator (1) does not exceed 0.06 (6%) for two load sensors, and for a 16-sensor MS-WIM system it is 0.01 (1%).

Fig. 4 shows the influence of the vehicle's speed on results of MV estimation. The virtual WIM site was equipped with 16 load sensors, and simulation was performed on the class B road. Both estimators exhibit lower sensitivity to change in speed than to change in the number of sensors. However, a tendency towards increase in both: the bias error (in module) and standard deviation, with the increase in speed, is observable.

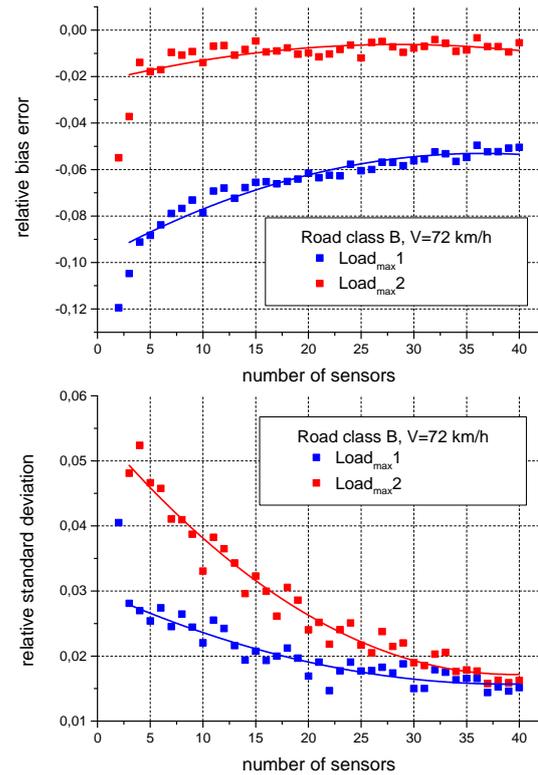


Fig. 3. Influence of the sensors number on the relative bias error and relative standard deviation of MV estimation

This effect can be simply explained: with the increase in speed increases also the value of the axle load dynamic component, that in turn results in the increase in the estimation errors, particularly the standard deviation of estimates.

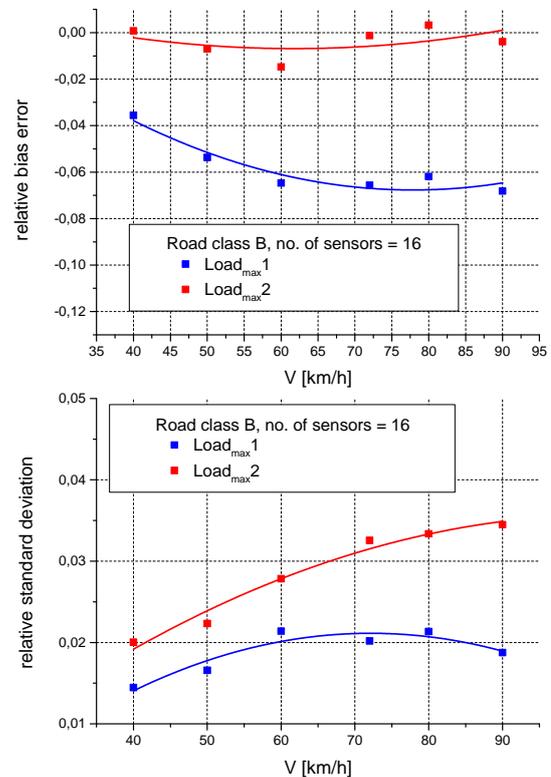


Fig. 4. Influence of the vehicle speed on the relative bias error and relative standard deviation of MV estimation

Fig. 5 shows the variability of relative bias error and standard deviation of the estimates of MV algorithms for roads in classes A, B and C, where class C is the lowest quality road. It was assumed that the vehicle is travelling at the speed of 72 km/h, and the WIM system acquires 16 axle load samples.

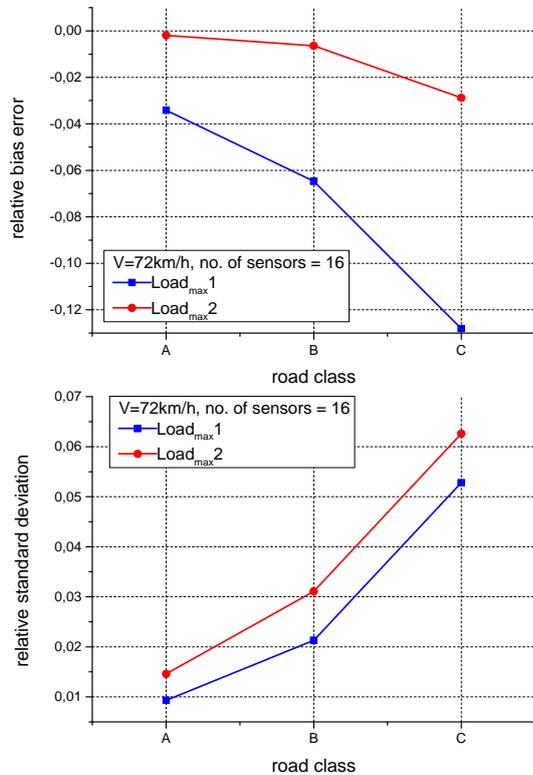


Fig. 5. Influence of the road class on the relative bias error and relative standard deviation of MV estimation

The poorer the road pavement, the larger are estimation errors. This premise confirms the rule that weighing systems should be installed on roads in the best class. As a consequence of the estimator (2) application to the 16-sensor system on the A class road, the value of bias error is below 1%, and standard deviation of estimation results is of the order of 1.5%.

4. EXPERIMENTS

Similarly to the analysis made during the simulations, was also performed the analysis of measurement data acquired from an instrumented vehicle. It is a multi-axle heavy goods vehicle with one axle equipped with sensors that enable continuous recording of this axle wheel dynamic load on the pavement. The measurements were carried out at the 125.8th kilometre of the motorway A12 in the Netherlands. The instrumented vehicle was travelling with constant speed of 80 km/h. Eight passes were performed: 4 passes with the instrumented axle static load of 11 tonnes, and 4 passes with static load 9 tonnes; solely the estimator (2) was investigated.

Fig. 6 shows characteristics obtained in effect of averaging four results of a given estimator, corresponding to each pass with the set static load value.

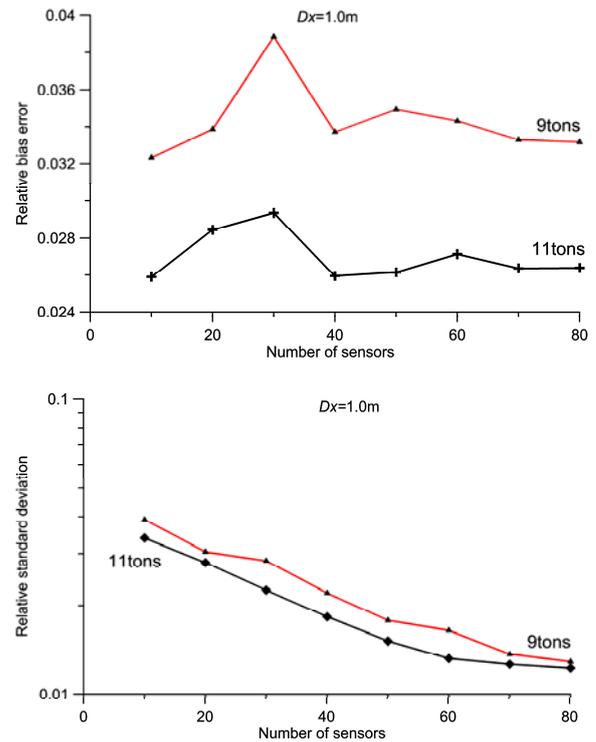


Fig. 6. Influence of the sensors number on the relative bias error and relative standard deviation of MV estimation (instrumented vehicle)

Such averaging facilitates formulation of conclusions about static properties of the investigated maximum axle load estimator:

- increasing the number of load sensors installed at the weighing site has no significant effect on the estimator bias error, nevertheless it reduces random variation of the determined estimates,
- an advantage of the proposed estimator (2) is a constant, independent on the number of sensors, value of the bias error and random variation decreasing with the number of sensors,
- the maximum load of a heavier axle is estimated with higher accuracy.

5. CONCLUSIONS

The paper presents concepts of estimating the maximum axle load of a vehicle in motion, based on measurement results obtained from MS-WIM systems. The problem posed that way may be compared to the estimation of maximum value of a low-band polyharmonic signal, sampled with insufficient sampling rate and extremely limited number of samples. Two statistical estimators of maximum value have been proposed. Their advantage is that they do not require additional information about e.g. the vehicle class or its speed.

The sensitivity of estimation errors to changes in the number of the WIM system sensors, vehicle speed and the road class has been investigated by means of simulation methods. In all considered cases the estimator (2) has a

smaller bias error than the estimator (1) but a larger standard deviation of estimates. Its bias error on a road of class A for the 16-sensor WIM is 1%. These conclusions should, however, be treated with reserve because whereas simulations reflect correctly the trends of characteristics and relations between estimators, the numerical values cannot be interpreted in a straightforward way. It should be bear in mind that the results have been obtained from simulation of an idealized weighing system which measures axle loads without errors. In fact, the results of measurement on a road will contain errors resulting from WIM system properties.

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