MS-WIM SYSTEMS OPTIMISATION METHOD

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ABSTRACT

Multiple-Sensor Weigh-In-Motion (MS-WIM) is one of the most suitable way to accurately estimate axles static loads using WIM at traffic speed. Research works were carried out since 1989 on MS-WIM. Each axle applies a vertical force varying in time on the pavement. This force will be designated as the impact force hereafter. Repeating the measurement of the impact force along the pavement with an array of strip sensors allows to sample this force. Appropriated algorithms based on different theoretical approaches were previously developed (Cebon, Winkler, WAVE project…) to get rid of the pavement-vehicle dynamic interaction effects and estimate the static weight. Those algorithms, applied to MS-WIM data, lead to accurate estimation of axle static weight.

The application of WIM data is wide. Indeed, a statistical analysis of those data allows to calculate traffic aggressivity and monitoring the traffic evolution year after year. WIM data can also be used for overloaded vehicle screening, which makes the enforcement much more effective. Finally, with accurate estimation of static axle loads, MS-WIM could meet automatic enforcement purposes.

Using a powerful truck/road dynamic interaction simulation software allowed to generate a large impact forces database. The choice of the influencing parameters for the achievement of this database aimed to be representative of the real in situ environment (pavement, mechanical, and driving characteristics).

This paper investigates an optimised MS-WIM array design, and particularly in term of sensor spacing specification.

INTRODUCTION

Many parameters as sensors number, sensor spacing, total length, sensors quality (noise), road characteristics (evenness, deflection, slope,…), define a MS-WIM array. All of them could affect the MS-WIM array efficiency. However, this paper will particularly investigate sensor spacing.

A simulation software was used to carry out this research. Indeed, truck impact forces were calculated along defined road profiles, and sampled according to a virtual MS-WIM array.

Usual algorithms were applied in order to evaluate the array design influence on the static weight estimation using the simulated samples.

Conclusions for MS-WIM array optimisation will be given, with respect to accuracy results.

SIMULATED DATA

It was decided to choose a simulation approach to provide impact forces data considering it is a cheap and comfortable 'sensor noise free' solution to control trucks parameters variations.

Simulation software

The software PROSPER (PROgram of SPEcification and Research components), developed by the French company SERA-CD, was chosen to simulate dynamic behaviour and interaction between trucks and road. This software was initially developed for military vehicles and is based on a 3D computation engine, with 29

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Degrees of Freedom, coupled and non linear with 600 variables. It allows varying geometry modelisation with different levels of complexity (according to purpose and available data).

Some parts of the software were validated by the DGA-ETAS (French Ministry of Defence) with real trucks (Delanne et al., 2003).

The truck model is built with pre-designed elements stored in user's libraries, such as loads, axle spacing, number of axles, etc. Tires are modelled with a Pacejka's model and PROSPER takes into account the ground inputs (2D or 3D road profile). Simulation options allow to assign a trajectory, speed, and all driving parameters.

Pneumatic model was designed according to Michelin specifications.

PROSPER simulates trucks dynamic behaviour, with several input parameters (such as mechanical truck characteristics, road profile, axle static load, load distribution in the truck, speed, etc).

The output parameter we were interested in is the resulting impact force for each axle.

Simulations carried out

Vehicles

The two trucks selection to be used for simulation was based upon French traffic path as found in (Jacob and Labry, 2002).

Two traffic samples were recorded on A9 motorway (Nimes-Perpignan) in 2001, by the concessionary company Autoroutes du Sud de la France (ASF), and on the A5 motorway (Paris-Langres), by the concessionary company Société des Autoroutes Paris-Rhin-Rhône (SAPRR). The truck type distributions are presented in figure 1.

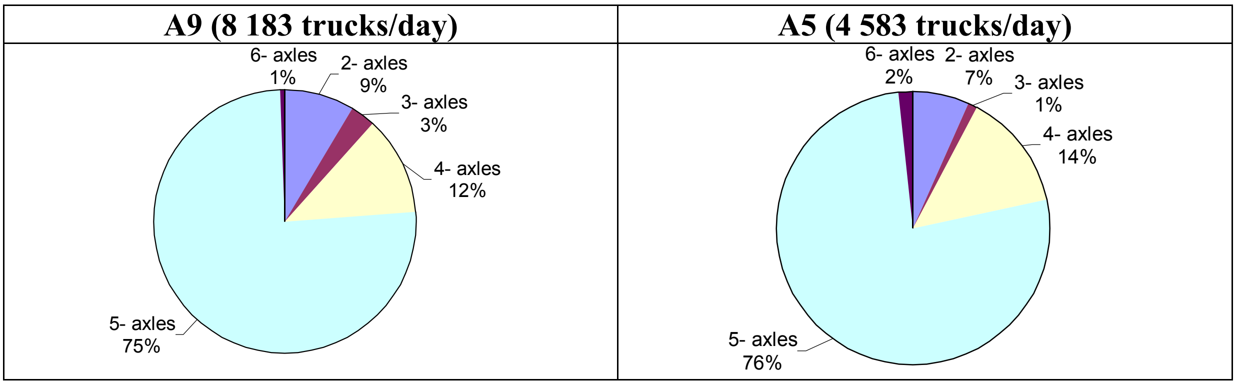


Figure 1. Percentage of each type of truck (Nb of axles) on two French motorways.

Traffic samples are mainly composed of 5-axles trucks (respectively 75% and 76% for A9 and A55). Then, about 13% of the heavy traffic are 4-axles vehicles, and around 8%, 2-axles vehicles.

In order to have both articulated and rigid vehicles, we have chosen to use a simulated articulated 5-axles trucks with 2 axles for the tractor and a group of 3 axles for the semi-trailer (Type 5), and a 2-axles rigid truck (Type 1) to represent this distribution.

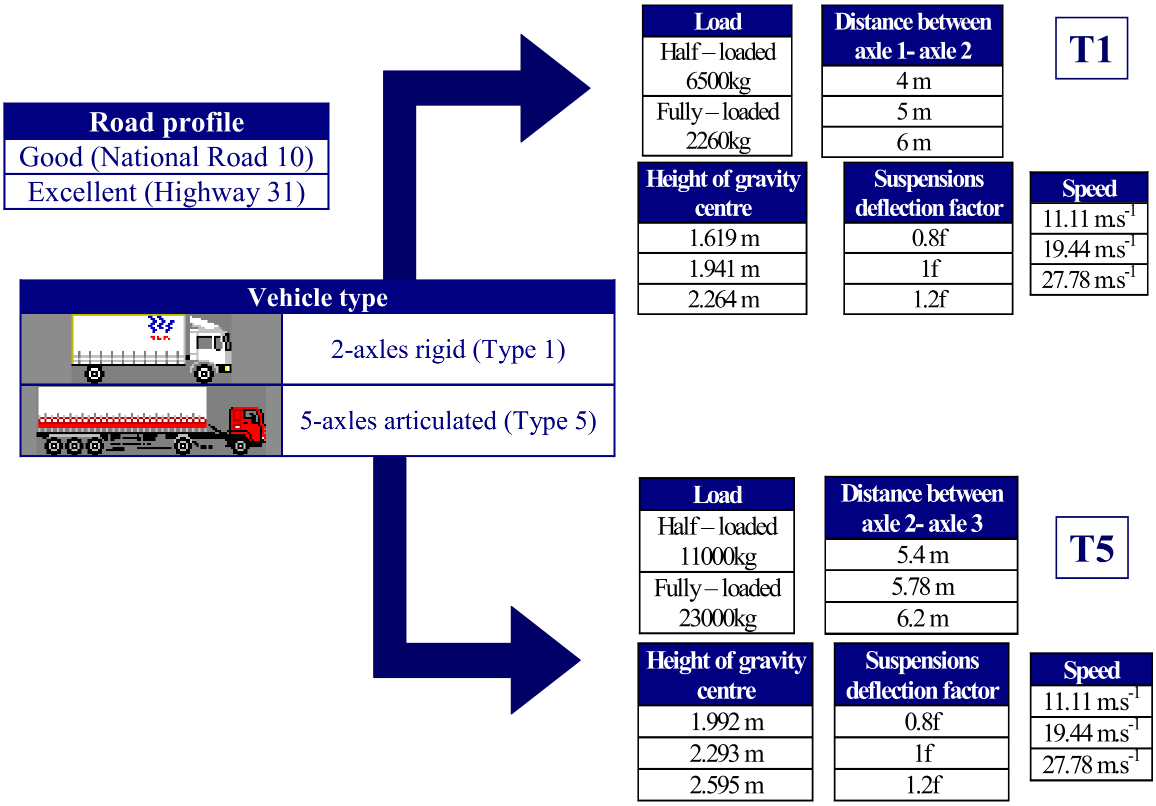
Environment

Two road profiles were chosen as representative of French roads. Indeed, as part of a PROSPER input, one can completely describe the pavement evenness; and such, we have provided the real measured road profiles.

National Road 10 (RN10) pavement fulfils the requirements of a class II (good) WIM site, according to the European Specification of WIM (COST323, 2002). The International Roughness Index (IRI) is 1.71 m/km, the APL (Analyseur de Profil en Long) rating is 7, 7 and 6 in the long, medium and short wavelengths.

Motorway 31 (A31) is classified as a class I (excellent) site according to the European specification of WIM. The IRI is 0.79 m/km, and the APL rating is 9, 9 and 10 in the long, medium and short wavelengths.

Figure 2 shows a summary of parameters used for 72 simulations (36 on RN10, 36 on A31) and for which the assumed influence on the truck impact force is strong.



Road profile
Good (National Road 10)
Excellent (Highway 31)

Vehicle type	
	2-axles rigid (Type 1)
	5-axles articulated (Type 5)

T1

Load
Half – loaded 6500kg
Fully – loaded 2260kg

Distance between axle 1- axle 2
4 m
5 m
6 m

Height of gravity centre	Suspensions deflection factor	Speed
1.619 m	0.8f	11.11 m.s^{-1}
1.941 m	1f	19.44 m.s^{-1}
2.264 m	1.2f	27.78 m.s^{-1}

T5

Load
Half – loaded 11000kg
Fully – loaded 23000kg

Distance between axle 2- axle 3
5.4 m
5.78 m
6.2 m

Height of gravity centre	Suspensions deflection factor	Speed
1.992 m	0.8f	11.11 m.s^{-1}
2.293 m	1f	19.44 m.s^{-1}
2.595 m	1.2f	27.78 m.s^{-1}

Figure 2. Summary of simulation program.

Thus, load, height of vehicle gravity centre, distance between axles, speed and suspension deflection factor are varying according to this simulation program.

An example of the suspension deflection variations (applied to the first axle of a type 5 tridem) according to factor f is presented in Figure 3.

Complete description of Prosper software, including model parameters and suspension description is available in (Schaefer, 2002).

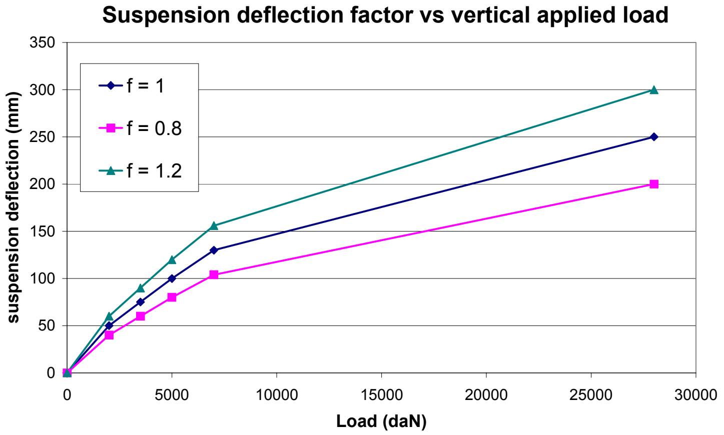


Figure 3. Suspension deflection factor for a type 5 tridem first axle.

MS-WIM ARRAYS

The calculated impact forces are sampled along the road profile such as they would be measured by a MS-WIM array of sensors (cf.Figure 4).

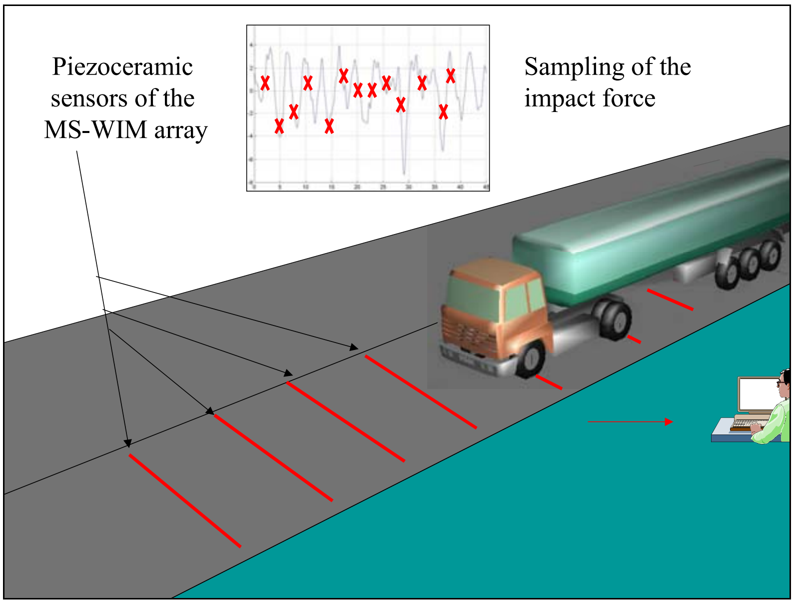


Figure 4. Sampling of the impact force by a MS-WIM array.

Several arrays composed with 16 WIM sensors were tested. Indeed, for enforcement purposes, COST323 class A for static weight estimation is aimed (COST323, 2002). Theory showed that at least 11 or 12 sensors were recommended to expect reaching this level of accuracy (WAVE, 2001). Furthermore, electronic devices associated to MS-WIM systems allows 2^n channels (each channel is linked to one sensor). Thus, accuracy and material concerns led us to study WIM arrays composed of 16 sensors.

The first sensor position was invariable along the path although arbitrarily chosen, and the sensors were uniformly spaced using different spacing.

Cebon's formula (Cebon and Winkler, 1991, Cebon, 1999) gives an optimised sensor spacing for small number of sensors, using a sinusoidal impact force model and a random noise. Theory was extended by Stergioulas et al. (2000) to larger number of sensors, using a two sine impact force model, and led to Stergioulas' formula.

An alternative method is proposed and consists in using simulated impact forces to calculate the optimal sensor spacing which minimizes the static weight estimation error, and which, as a result, includes trucks dynamics and road profile influence.

Cebon's and Stergioulas' formulas

Theoretical studies on MS-WIM using a 'SAve' (Simple AVErage) method were carried out by (Cebon and Winkler 1991, Cebon 1999). An optimal design of a n-sensors (uniformly spaced) MS-WIM array was defined by modelling the impact force by a single sine and random noise. A formula was proposed to calculate the optimum spacing d of n sensors, as a function of n, of the mean traffic velocity V (m/s) and of the mean bounce motion frequency of the trucks f (Hz) :

$$d = \frac{2.(n-1).V}{f.n^2} \qquad (1)$$

This theory determines the envelope error of the MS-WIM estimation according to the sensor spacing. Formula (1) ensures the calculated spacing will be located on the smooth part of the envelope error plot, which is depicted on Figure 5 (non-dimensional spacing Delta = d/(V/f), with d taken as the spacing (m), V the mean speed (m/s), f the body bounce frequency (Hz)).

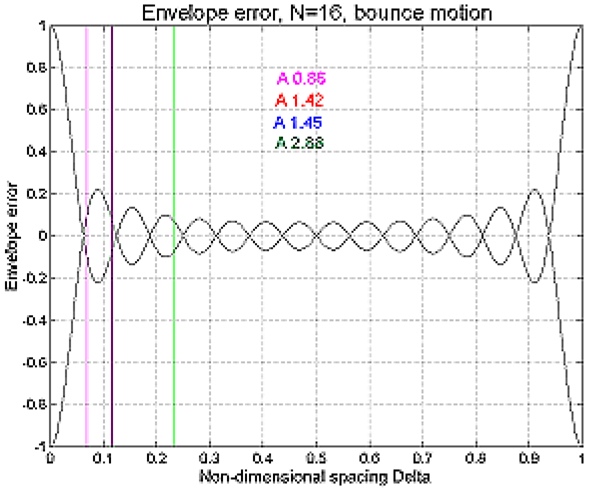


Figure 5. Envelope error versus non-dimensional sensor spacing.

Extension of this theory to two sine waves model led to formula (2) taking into account both bouncing (f_1) and axle hop (f_2) frequencies (Stergioulas et al. 2000):

$$d_2 = \frac{V}{2.n}\left(\frac{1}{f_1} + \frac{n-1}{f_2}\right) \tag{2}$$

Formula (1), with a mean velocity of 22.2m/s, a body bounce frequency of 1.8Hz provides for the 16 sensors array an optimal spacing equal to 1.45m (array A 1.45, total length 21.75m).

Formula (2) with the same values and axle hop frequency of 10Hz gave an optimal spacing of 1.42m (array A 1.42, total length : 21.3m).

The closeness of both spacings proves that the optimal spacing for the axle hop frequency falls in the acceptance domain of formula (1) for bounce frequency. It may also be assumed that the bounce motion is dominant. Both arrays were tested in spite of the very close calculated spacing values.

Two more spacings were evaluated : 0.86m and 2.88m (resp. A 0.86, length of this array : 12.9m; A 2.88, length of this array : 36m). The lower corresponds to a minimum acceptable spacing, but not optimized according to formula (1). The larger is the double of the optimal spacing according to formula (1) and (2), falls in the acceptance domain, and was chosen to evaluate the influence of an increase of the array length. This array is expected to be less sensitive to the road profile variations, as the signal is averaged on a longer distance. Moreover, it was shown in OECD/DIVINE project (Jacob and Dolcemascolo 1997) that arrays with length about 30-40m would better fit the long wavelengths of the road profile.

Proposed array design optimisation method

The advantage of this method compared to formula (1) is the use of impact forces calculated with both trucks dynamic and road profile.

The part related to the trucks dynamic varies from one vehicle to the other, but the part related to road profile shows relevant similarities for all the trucks. This spatial repeatability phenomenon was shown in the OECD/DIVINE project (Jacob and Dolcemascolo, 1998).

Taking into account spatial repeatability led to average impact forces, and to search for the sensor spacing which minimizes the mean error and standard deviation of the static weight estimator. To find this optimum spacing, the impact factors (equation 2) where averaged for all simulated trucks according to three different criteria : gross vehicle weight (GVW, taken as the sum of impact forces of each axles), single axles SA, and axles of group AoG.

$$IF = \frac{F/g - W_s}{W_s} * 100 \tag{2}$$

where IF is an Impact Factor, F is the impact force (force applied by a wheel or an axle on the road) in Newton, g is the gravity intensity (g= 9.81 m.s^{-2}), and W is the axle static weight.

Thus, the impact factor represents the relative error between the dynamic force and the static load of the axle or the wheel.

The averaged impact factor is sampled into 16 points, at each sensors location. The values at these locations were averaged, and, in order to evaluate the performance of the array, the mean error m and the standard deviation s of the error were calculated. Then the static load estimator, i.e. the sensor spacing, was chosen to minimize m^2+s^2 (m : mean, s : standard deviation).

Figure 6 shows the results for gross weights.

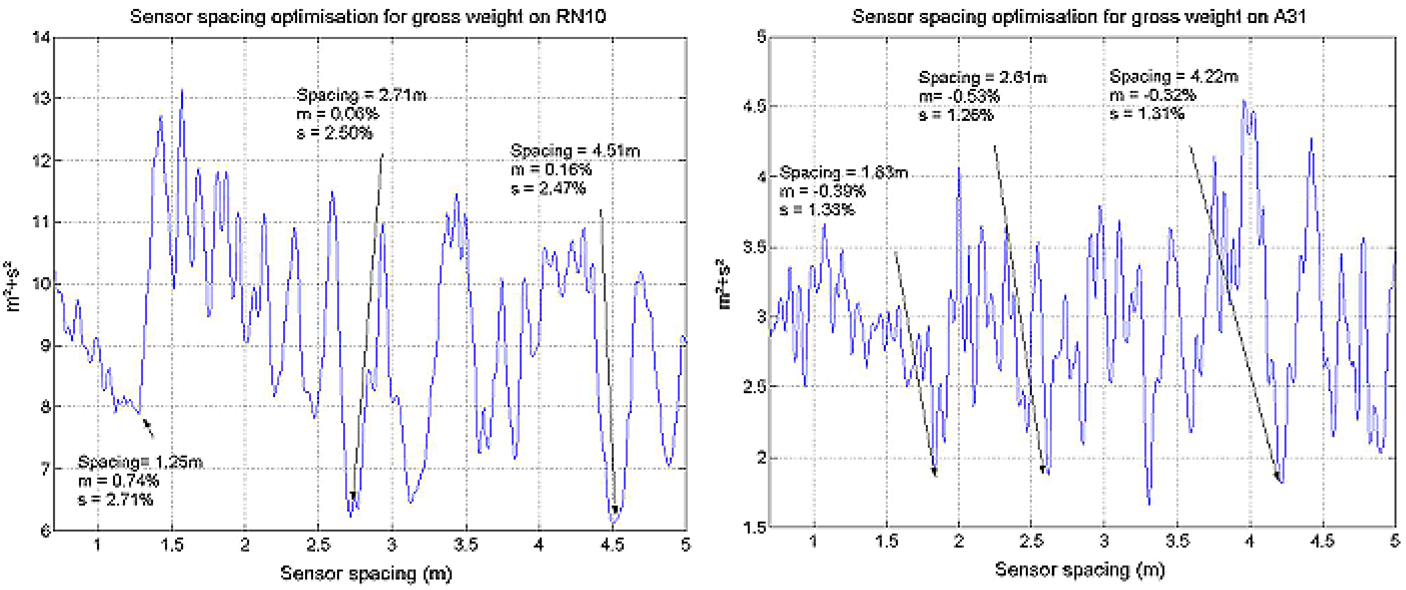
Robustness of the method was checked using different truck simulation samples on the same road profile. These different samples led to the same optimal spacing (differences of less than 2cm) which tends to prove that the method is rather independent on the trucks sample.

Moreover, each criterion (SA, AoG and GVW) led to about the same optimised spacing (slight differences for the group of axles). Indeed, while the optimal spacings remain close each from the other for each criterion, m^2+s^2 does not increase too much compared to the minimum value.

Three optimised spacings were chosen for each road profile, taking into account the array length (short, medium, long). They appear on Figure 6 and are summarised in Table 1.

This method optimises the sensor spacing using a Simple AVEraging estimation (see paragraph 4), similarly to formula (1). At this stage, the effects on other algorithms is unknown.

Sensor spacings according to formula (1) and formula (2) were located on those plots. Results are not displayed here, but they never correspond to any minima. They seemed 'randomly' distributed on these plots and no correlation between the two methods could be shown.



a – Gross weight, RN10

b – Gross weight, A31

Figure 6. Optimisation of the sensor spacing for each road profile.

Table 1. Results for optimised distance spacing.

RN 10	**A 31**
Opt1.25 : d= 1.25m (Length : 18.75m)	*Opt1.83* : d=1.83m (Length : 27.45m)
Opt2.71 : d=2.71m (Length : 40.65m)	*Opt2.61* : d=2.61m (Length : 39.15m)
Opt4.51 : d=4.51m (Length : 67.65m)	*Opt4.22* : d=4.22m (Length : 63.30m)

MS-WIM ALGORITHMS

MS-WIM algorithm as detailed hereafter were applied to these raw data. Signal Reconstruction (SR) and Maximum of Likelihood (LK) methods were developed within the WAVE European project (WAVE, 2001).

For comparison of static weight estimation algorithms, a random noise is added to simulate real sensors behaviour. But this study aims to compare several array designs and the influence of a random noise was considered as disadvantaging our analysis, that is why raw data were used.

The simple averaging method (SAve)

Assuming that the spatial mean of the axle impact forces is equal to the static axle load, leads to average these dynamic loads, measured by a set of uniformly spaced sensors of a MS-WIM array. This estimation by a "Simple Average" is denoted here as 'SAve' method.

The signal reconstruction and Kalman filtering method (SR)

This method was developed in the LCPC (Sainte-Marie et al, 1998). This deterministic approach consists of a reconstruction of the continuous dynamic axle impact force signal, using the sample of impact forces measured by each sensor of the MS-WIM array. Then, the static axle load is estimated by the mean of the reconstructed signal, on a given road length (L). L depends on bouncing and rolling frequencies, which are estimated by an extended Kalman filtering procedure.

The maximum of likelihood method (LK1, LK2)

This method was developed by CUED (Stergioulas et al, 1998) and is a probabilistic method based on a Maximum of Likelihood estimator and a signal modelling of the dynamic forces. The theoretical analysis considers two generic vehicle models and simple approximations: (LK1) a quarter car model, whose tyre force spectrum can be reasonably approximated by a single sine wave (low frequency mode (1.8-4 Hz) corresponding to the body vehicle bounce), and (LK2) a 'walking beam' model, whose tyre force spectrum can be approximated by two sine wave components (one for low frequency mode and the other for high frequency mode (10-15 Hz) corresponding to the axle hop).

Then, assuming that a random noise is added to the tyre force signal, the Maximum of Likelihood method gives an estimation of the model parameters: static weight, the signal amplitude(s), phase(s) and frequency(ies).

ACCURACY RESULTS

Accuracy of the static weight estimation by the algorithms presented above is evaluated by the delta min value (d_{min}), according to the European WIM Specifications (COST323, 2002).

d_{min} is the half-width of the confidence interval for a required minimum level of confidence defined by the Specifications. It is calculated for different criteria : Gross Vehicle Weight (GVW), Group of Axles (GoA), Single Axles (SA), and Axles of a Group (AoG).

For legibility concern, not all the optimised array results are displayed. Indeed, it was shown that on RN10 (national road), Opt2.71 and Opt4.51 provided very similar results, that is why Opt2.71 is the only one presented here. On A31 (motorway), Opt2.61 and Opt4.22 were similar as well.

These similarities tend to prove that with close values of m^2+s^2, and a given array length threshold, results are equivalent.

Besides, due to very good pavement evenness on A31, differences between results for each sensor spacing were not considered as significant, and will not be presented here.

Figure 8 presents the results for all truck types (Type 1 + Type 5) on RN10 and for each estimation algorithm.

Shorter arrays (Opt1.25 and above all A0.86) seem less appropriated for all estimation methods. Longer arrays A2.88 and Opt2.71 provide very good results, particularly for gross weights, whatever the static weight estimation method.

Total length of the array seems to be a relevant parameter for accuracy improvement, and should be as long as possible within the range investigated.

Particular bad performance of A0.86 proves the importance of appropriate choice of sensor spacing, as this array's results can be more than twice less accurate.

SR method is expected by theory to be insensitive regarding to sensor spacing. Indeed, all arrays allow to reach equivalent level of accuracy, except with A0.86. This phenomenon might be correlated to an 'array length threshold' above which all arrays provide equivalent results, but below which the impact force sampling is not sufficient to reconstruct the signal correctly.

This threshold might then be lower than for other method as one can notice that Opt1.25 array's performance is not so far from other arrays, contrary to the other methods.

Not significant difference between the array spacings calculated with formula (1) or formula (2) (A1.42, A1.45) is noticed. The large number of sensors seems to smooth the importance of taking into account both axle hop and body bounce motion. This can be concluded both from the very close spacing values (1.42m and 1.45m) and with the performances observed.

Optimised array Opt2.71 provides slightly better results than arrays with sensor spacing calculated with formula (1) or formula (2).

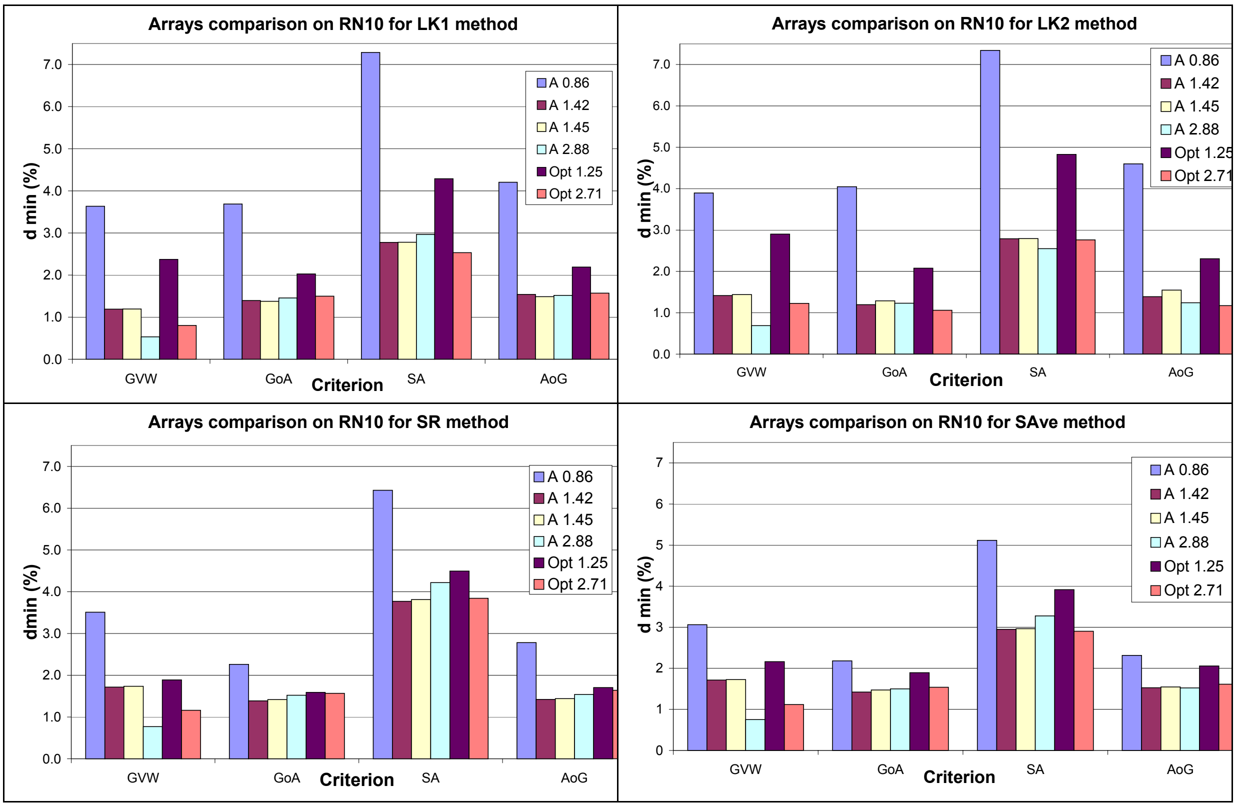


Figure 8. Arrays comparison on RN 10 – Type 1 and 5 trucks.

CONCLUSIONS

A new method was presented to calculate optimal sensor spacing of MS-WIM arrays. The accuracy obtained with these arrays was compared to the accuracy obtained with other arrays designed by formulas proposed in the literature, or randomly designed.

Accuracy results have shown that :

- For excellent pavement evenness, differences between the array spacings were not significant.
- Static weight estimation algorithms were similarly influenced by sensor spacing, except SR which is much less sensitive to the sensor spacing and seems to be only affected by very short arrays.
- Whatever the sensor spacing calculation method, particular attention should be paid to the array length, which should be long enough with respect to the road profile wavelength.
- In case of MS-WIM sites with good or poor road profiles, with large number of sensors, it seems useful to check that the sensor spacing is not a multiple of the axle hop or bounce wavelength using formula (1) or (2) design. The proposed design method by impact forces simulations taking into account the road profile and optimisation of the sensor spacing, lead to slightly better accuracy, given that the total array length is above 30 to 35 m.

Thus the newly developed method for sensor spacing calculation was proved to be effective and further studies should be carried out with noisy impact forces samples.

Further research works will also have to be carried out to correlate this experimental method to theoretical truck models, and so to determine the length threshold allowing to improve the efficiency of MS-WIM systems.

Other characteristics of an MS-WIM array (number of sensors, sensors quality, first sensor location,…) could be undertaken by future works, in order to be also optimised.

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