Vehicle Configuration Influences on Weigh-in-Motion Response

P. E. VAN NIEKERK AND A. T. VISSER

Statistics on axle and vehicle masses traditionally have been collected by stopping and weighing vehicles on axle or whole-vehicle weighers. This technique is still applicable but only on roads carrying low truck volumes or in instances in which only a small sample of the population is required. On heavily trafficked roads this technique is extremely hazardous. Because of the inherent limitations of static weighing, considerable developments have taken place in the last decade on systems that permit the collection of data on axle and vehicle masses. These data are recorded while the vehicles travel at normal highway speeds without interference to the traffic stream. These systems are commonly known as weigh-in-motion (WIM) systems. The dynamic pavement loading, by simulation, of various vehicle configurations on a range of pavement roughnesses where WIM installations could be made are reported. In the evaluations the mass variations are attributed to the dynamic influences, although the precision of the measuring system is not taken into account. The simulation procedure is presented and its use is justified by comparing simulated results with measured axle masses. Variation in all the axle loads of various vehicles along sites that typically could be appropriate for WIM, ideally having a pavement serviceability index greater than 3.0, are presented. The influence of the systems flush with the surface and placed on the surface are considered. The effectiveness of WIM to measure vehicle masses is then presented. Finally the implications of these results of WIM accuracy, calibration, and weighing are discussed.

Statistics on axle and vehicle masses traditionally have been collected by stopping and weighing vehicles on axle or whole-vehicle weighers. This technique is still applicable but only on roads carrying low truck volumes or in instances in which only a small sample of the population is required. On heavily trafficked roads this technique is extremely hazardous. Because of the inherent limitations of static weighing, considerable developments have taken place in the last decade on systems that permit the collection of data on axle and vehicle masses. These data are recorded while the vehicles travel at normal highway speeds without interference to the traffic stream. These systems are commonly known as weigh-in-motion (WIM) systems.

A number of WIM systems are available on the market. For example, eight different systems are under evaluation on I-95 at the Pennsylvania and Delaware border (*1*). These systems are either built into the pavement flush with the surface or fastened onto the surfacing. A range of technologies is employed: for example, strain measurements, capacitive sensors, and piezoelectric systems.

P.E. van Niekerk, VIAED, P.O. Box 35256, Menlopark, 0102, South Africa. A.T. Visser, Department of Civil Engineering, University of Pretoria, Pretoria, 0002, South Africa.

Although attempts are made to calibrate the systems before installation, calibration to assess the local site conditions is essential (*2*). Previous experimental work (*3*) also showed that calibration with one vehicle type does not necessarily apply to other vehicle configurations. More recently it was reported (*4*) that the front axle of a five-axle rig is consistently underreported. A need therefore exists for a fuller understanding of dynamic axle loading effects to be able to compensate for the inconsistent results that are found in practice.

Recently a research project on dynamic heavy vehicle influences was completed (*5*), and this provides a basis for addressing the issues mentioned above. The aim of this paper is to report on the dynamic pavement loading, by simulation, of various vehicle configurations on a range of pavement roughnesses where WIM installations may be made. In the evaluations the mass variations are attributed to the dynamic influences although the precision of the measuring system is not considered.

The paper briefly presents the simulation procedure and justifies its use by comparing simulated results with measured axle masses. Variation in all the axle loads of various vehicles along sites that typically would be appropriate for WIM measurements [pavement serviceability index (PSI) > 3.0] are presented. The influence of systems flush with the surface and placed on the surface also is considered. The effectiveness of WIM to measure vehicle masses is then presented. Finally the implications of these results on WIM accuracy, calibration, and weighing are discussed.

METHOD OF ANALYSIS

A wide range of factors influence the magnitude of the dynamic loading effects and their spatial distribution (*5*). However, only the following factors are relevant for normal highway vehicles traveling over WIM sites and were considered in this study:

- Vehicle configuration;
- Vehicle speed;
- Road roughness; and
- WIM equipment arrangement.

A vehicle simulation program, tire force prediction program (TFP) (*6*), was used to determine the relative influence of each of these factors. The program's suitability was validated by comparing the program output with measurements obtained during field tests.

Because this comparison was found to be acceptable, the simulation program was used to determine the influence of the aforementioned factors. The vehicle configurations included

- A two-axle rigid truck: Truck Type 1;
- A three-axle rigid truck: Truck Type 2;
- A two-axle tractor with a single-axle trailer: Truck Type 3;
- A two-axle tractor with a tandem trailer: Truck Type 4;
- A two-axle tractor with a tridem trailer: Truck Type 5; and
- A three-axle tractor with a single-axle trailer: Truck Type 6.

To permit the ready comparison of results for each vehicle, the responses for each of the vehicle configurations at each site were determined and normalized by dividing the dynamic load by the static axle load.

Vehicle speed is the primary determinant of the dynamic loading and two vehicle speeds, namely 5.5 and 44 km/hr were used in evaluating vehicle effects, but 80 km/hr was used to evaluate speed effects. To assess pavement conditions, three different road profiles with a riding quality of 3.8, 3.3, and 3.0 PSI were used.

The normalized responses were determined at regular 150-mm intervals along the road profiles, and these responses were then used to show the variation of the dynamic loading along a road. The influence of different WIM installations was handled similarly, except that the dynamic load on the WIM was compared.

COMPUTER SIMULATION TECHNIQUES

TFP Program

The TFP program is designed to enable the highway engineer to predict tire forces that occur as a vehicle travels along a road in a straight line. The road profile is defined by points at 150-mm intervals representing the elevation of the road for the two wheel-paths.

The TFP program can simulate four basic vehicle configurations:

- A rigid truck;
- A tractor-semitrailer combination;
- A tractor-semitrailer combination with one full trailer; and
- A tractor-semitrailer combination with two full trailers.

The tire forces predicted by the TFP program are for a road section traversed by a vehicle at constant velocity. These tire forces are applied at the tire-pavement interface. The tire characteristics and inflation pressures are quantified through the tire spring rate. No turning or braking maneuvers or roll effects can be simulated. This program is useful for the formulation of policy governing highways that normally involve vehicles moving at constant speed along a straight section of roadway.

The model used consists of two planar rigid-body inertial masses representing the tractor sprung mass and the semi-trailer sprung mass. Each vehicle component's mass is constrained to move vertically (heave) and rotate (pitch) in the direction of travel. The vehicle suspension is represented by a parallel combination of springs, a viscous damper, and a coulomb damper at each axle. The viscous dampers represent shock absorbers and in practice appear only on the front suspensions. The coulomb dampers exert a constant force against the direction of relative motion between the tire mass and the vehicle mass.

The model of the tractor–semitrailer–full trailer used in developing the program is shown in Figure 1. Various profiles that previously had been surveyed were selected and analyzed to determine which would be used for the simulations. From the rod and level data for the sections the root-mean-square vertical acceleration (RMSVA) was determined (*7*). From a correlation with the RMSVA a PSI was calculated for each section. Finally three sections were used in the simulations. The three profiles included a rough profile (PSI = 3.0), a medium profile (PSI = 3.3), and a smooth profile (PSI = 3.8).

The need for assessing the pavement profile is highlighted by previous findings (*8*) that the dynamic effects of the pavement profile for approximately 150 m in advance and 30 m after the WIM site could affect the response at that point. The 30-m length after the WIM is to ensure that the influence of dynamics from the leading axles on the trailing axles is considered.

Validation of Simulation Program

The TFP computer simulation program was verified by using more general simulation programs and comparing these results with those from field tests. One particular field comparison incorporated the use of piezoelectric film strips to correlate simulated results (*6*). From these tests it was concluded that the TFP predictions bound the range of field data.

Simulation Process

The simulations undertaken for the current study involved the determination of the force profiles for each of the vehicle types at a specific speed and over a specific road profile. The dynamic forces were determined at 150-mm intervals and then integrated to determine the gross vehicle mass (GVM) on a 600-mm section because this is the approximate width of WIM platforms. These GVM values were determined for consec-

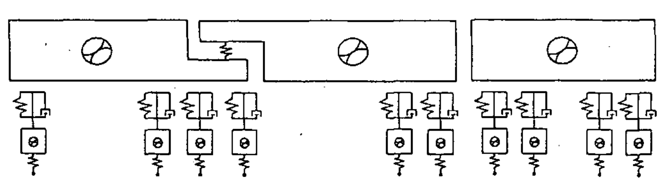

FIGURE 1 TFP tractor–semitrailer–full trailer model.

utive 600-mm sections by moving the 600-mm section forward in 150-mm intervals.

Once this was completed for all the vehicle types, each GVM profile was normalized by dividing the dynamic load by the static mass of the individual vehicles. The various normalized distributions were then plotted to determine whether any similarity existed for the various vehicles. Variation of the relative static mass of a particular vehicle from that of a rigid calibration vehicle (two-axle rigid truck) was also determined. This profile could be used to assess the error resulting from the use of a specific vehicle to calibrate WIM instruments at a particular site.

A further analysis of the dynamic response of the front and leading rear axle of all the vehicles was done at two different speeds and over three road profiles. The response of corresponding axles in various vehicles as well as the response of various axles of specific vehicles was compared.

SIMULATION RESULTS

Vehicle Configuration

Table 1 presents the simulation of the gross vehicle mass for the various vehicle configurations traveling over a medium profile at a speed of 44 km/hr. Furthermore, as a basis for comparison, the deviation from that of a two-axle vehicle was determined by subtracting the deviation from the static of the two-axle vehicle from that of the other vehicle configurations at each simulation point along the profile. This gives an indication of the error that would be made if only a two-axle vehicle were used to calibrate the WIM equipment.

From the GVM simulation analysis results the following were found:

- The dynamic component of the GVM is not constant for all types of vehicles.
- No particular vehicle can be taken to represent the worst or best dynamic influence throughout the road section analyzed. The same vehicle does not necessarily retain the same relative ranking for all the profiles considered.
- The variation of the relative response of a particular vehicle from that of the standard vehicle (Truck Type 1) is not constant throughout a particular profile.
- There appears to be no similarity in the responses of the various tractor-trailer combinations when compared with both the standard vehicle and other trailer combinations.
- At 5.5 km/hr all the vehicles' response profiles lie within a very narrow range of +101 to −99 percent of the static load.

When considering the relative dynamic influence of various axles of a vehicle the following were observed:

- The two-axle rigid vehicle's front and rear axle follow a similar pattern, with the rear axle experiencing the higher relative loads. This effect is expected because the rear-axle response at a specific point along the profile is influenced by the response of the preceding axle to that same point, whereas the reverse is not true. This tendency can be seen in Figure 2, which shows the dynamic responses of the individual axles of a two-axle rigid truck traveling at a speed of 44 km/hr over a profile of PSI = 3.8.
- Relative responses for tractor-trailer combinations also show similar patterns for the front and rear axles, but these patterns are not similar to those of the standard vehicle. Peak relative responses for the various vehicle configurations occur at different points along the profile.
- The tractor-trailer combination's responses do not show constantly higher or lower responses for an axle at a particular point. At some points the front axle may have a higher relative response than the rear axle; at other points the contrary may be true. Figure 3 shows the dynamic responses of the individual axles of a two-axle tractor with a single-axle trailer.

Vehicle Speed and Road Roughness

Influence on GVM

The simulation results obtained for a two-axle rigid vehicle traveling over the three profiles considered and at speeds of 5.5, 44, and 80 km/hr are summarized in Figure 4. The following was observed:

- The speed of the vehicle greatly influences the dynamic response. The response of Vehicle 6 traveling at 5.5 km/hr on a rough profile (PSI = 3.0) deviates from the static GVM within a range of +3 percent. Traveling at 44 km/hr the same vehicle's response deviates from the static GVM within a range of +15 percent to −15 percent of the static GVM.
- No particular vehicle can be taken to represent the worst or best relative dynamic influence throughout the section analyzed. The same vehicle does not necessarily retain the same

TABLE 1 Dynamic GVM Response of Various Vehicles Traveling at 44 km/hr over a Profile of PSI of 3.0

Vehicle configuration	% Deviation from static			% Deviation from standard		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Truck type 1	15,0	0,0	8,8	0,0	0,0	0,0
Truck type 2	4,6	-5,1	-1,9	13,2	5,1	8,5
Truck type 3	8,6	-8,2	0,1	19,7	-0,1	8,6
Truck type 4	4,6	-6,1	-1,7	11,5	4,9	9,0
Truck type 5	5,0	-5,9	-0,2	14,0	3,6	9,3
Truck type 6	8,2	-1,4	3,5	11,0	0,2	6,0

relative ranking for all the profiles considered or throughout a particular profile.

- The speed of the vehicle greatly influences the relative dynamic response. The relative response of a two-axle tractor with a single-axle trailer traveling at 5.5 km/hr on a smooth profile (PSI = 3.8) lies in a range between 98 and 102 percent of the static GVM. Traveling at 44 km/hr the same vehicle's response lies within a range between 91 and 109 percent of the static GVM.

Influence on Individual Axles

The dynamic component is influenced by the profile of the road surface. A specific change in the profile does not, however, influence all the vehicle types in the same manner. Figure 5 shows the variation in the dynamic response of the rear axle of a two-axle vehicle for various road profiles at a PSI of 3.0, 3.3, and 3.8, respectively.

WIM Equipment Arrangement

Two types of WIM systems were investigated. One was a plate installed flush with the road surface, and the other was a capacitive mat placed on the road surface. Simulations were done on the three previously described profiles, and the axle loads were determined on a 600-mm planar section at a particular distance along the road section. The simulations were then repeated after the 600-mm planar section had been raised by 6 mm to represent a WIM mat placed on the road surface. These simulations were undertaken at a vehicle speed of 44

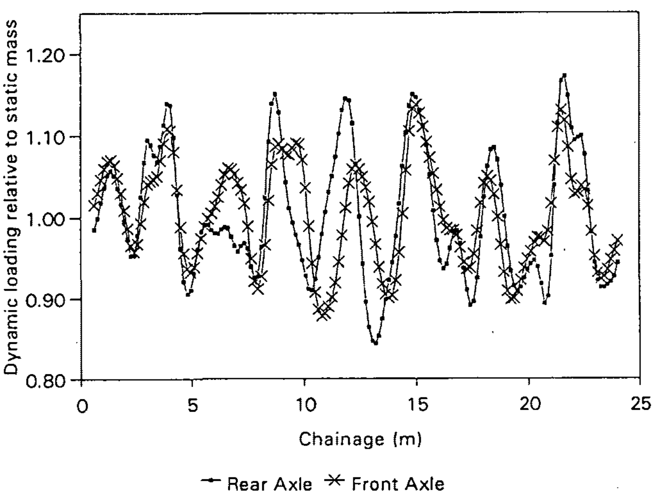

FIGURE 2 Dynamic responses of individual axles of two-axle truck traveling at 44 km/hr over profile of PSI of 3.8.

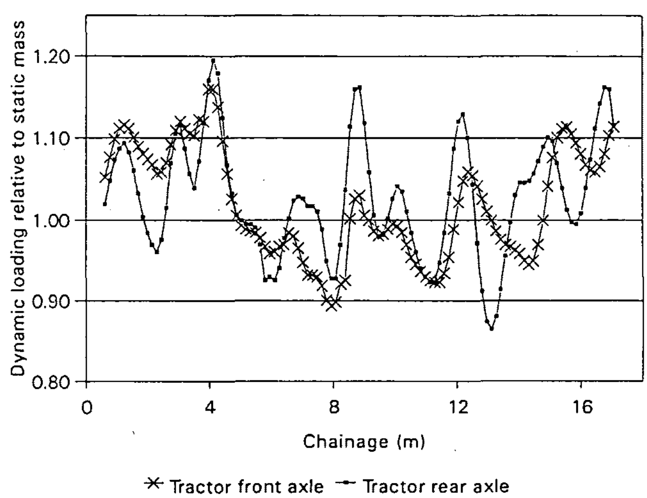

FIGURE 3 Dynamic responses of individual axles of two-axle tractor with single-axle trailer traveling at 44 km/hr over profile of PSI of 3.8.

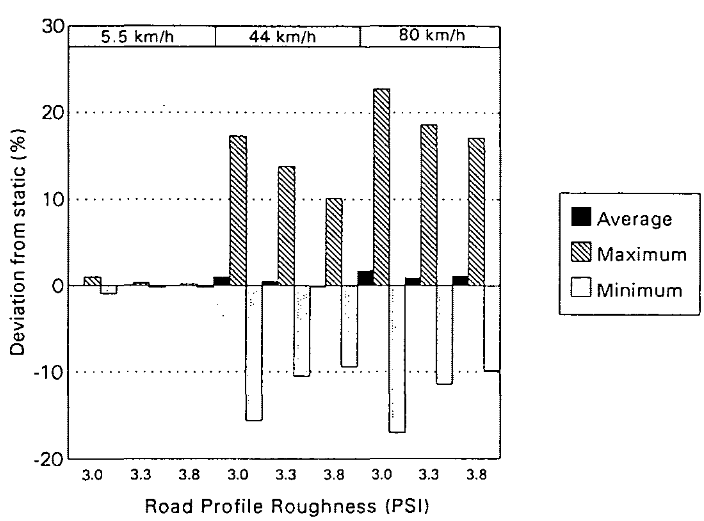

FIGURE 4 Dynamic response (GVM) statistics for two-axle truck traveling over range of profiles at three different speeds.

km/hr and from the previous results it is evident that the dynamic response found would increase as the vehicle speed increased.

The relative responses of the individual axles of a range of vehicle types, traveling over a 6-mm-thick WIM installation is shown in Figure 6. These were determined for a traveling speed of 44 km/hr and a road roughness PSI of 3.3.

For all the profiles considered and for all the vehicles simulated there was an increase in the dynamic response of all axles when the mat was placed on the road surface. This increase of between 6 and 13 percent was evident for all axles and on all profiles. This increase is however compensated by the calibration of the equipment. After correction this would translate to a maximum 7 percent deviation from static.

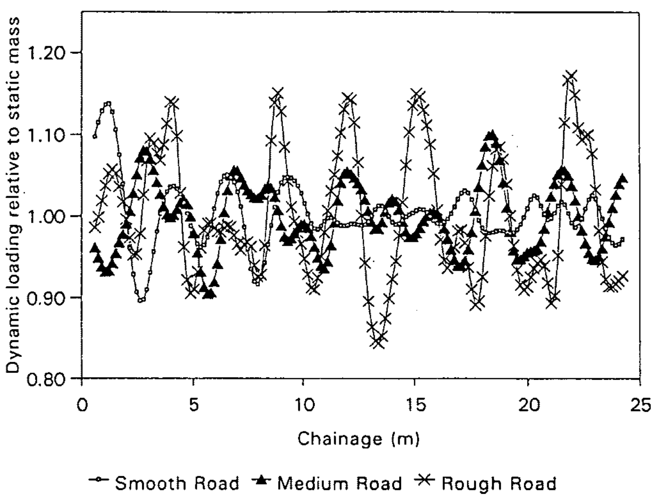

FIGURE 5 Dynamic response of rear axle on two-axle vehicle (44 km/hr).

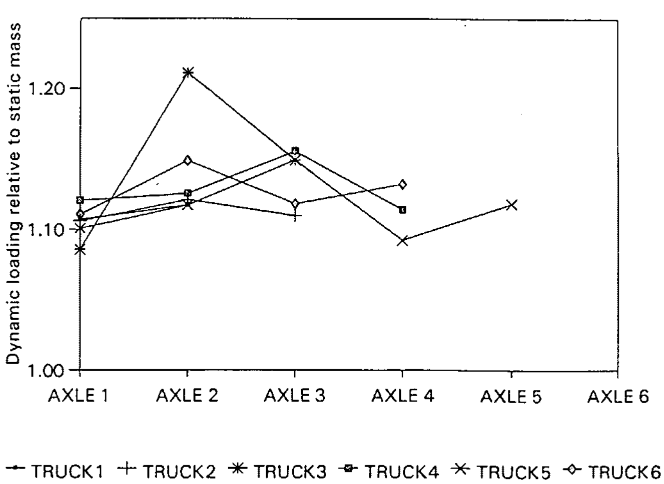

FIGURE 6 Relative response of individual axles of various vehicles traveling over 6-mm-thick WIM installation (road PSI = 3.3) at 44 km/hr.

The WIM results were determined over a 50-m road section. For the raised WIM the capacitive mat was moved forward in 600-mm increments, and the responses were determined for each position. The simulation results showing the deviation from the static load for a two-axle rigid truck traveling at 44 km/hr are summarized in Figure 7.

The following were found:

- For the WIM mat placed on the surface there was no generalized tendency for the dynamic load to move closer to the static axle load as the pavement roughness improved. For the mat placed flush with the surface the simulation yielded results that did not necessarily show the same tendencies as were shown for the WIM mat simulations.
- For both the raised and flush arrangement the front axle's relative response did not necessarily produce the smallest spread for the range of vehicles considered. No one specific axle was found to produce the best case throughout. The finding that the lowest variance between static and dynamic weight occurs in the second or third axle of a loaded five-axle semitrailer seems to hold (*4*). The axle with the lowest variance is, however, not always the same.
- There was also no relationship between the front axle's responses and those of the other axles. The front axle's responses could thus not be used to determine or predict the accuracy of any other axles. Any calibration of the WIM equipment would thus have to incorporate both the vehicle configuration and the axle number.
- For the smooth profile and for the case in which the WIM apparatus is placed flush with the surface, the front axle's responses were nearest to the responses of the static axle load.

CONCLUSIONS

Vehicle Configuration

The simulations undertaken again show that the use of any one specific vehicle to calibrate the WIM equipment can lead to serious errors. The suitability of a specific vehicle for use as a calibration standard is influenced by the road profile, the WIM arrangement, and the calibrating and operating speed.

The general approach of using a multiaxle vehicle for calibration is confirmed. The calibration would have to allow for both the vehicle configuration and the axle number when determining the correction to be used to determine the static load.

Vehicle Speed

The speed of the vehicle being weighed influences the variation of the response along a road section. As the speed increases the variation in response also increases. The specific increase varies from axle to axle and from vehicle configuration to configuration. The multiaxle vehicles generally have one axle that is least influenced by the speed. However, which specific axle is applicable is not always consistent and varies with the speeds considered.

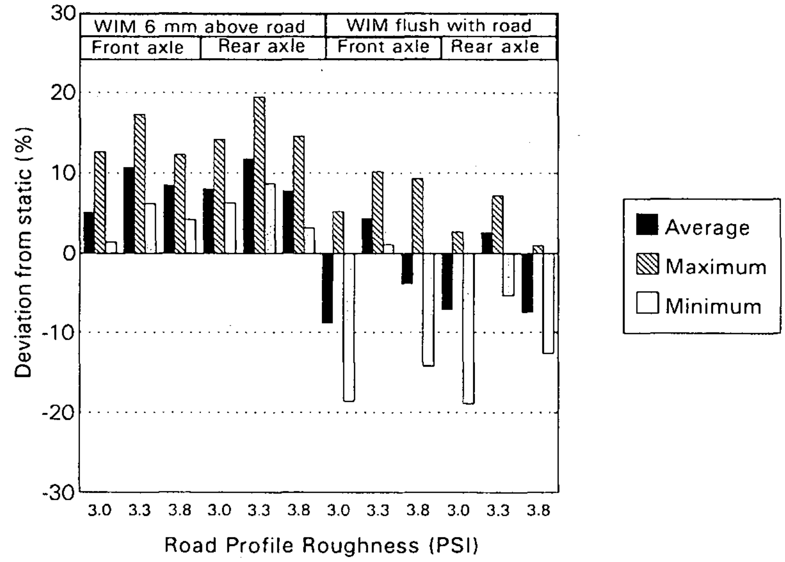

FIGURE 7 Dynamic response of two-axle vehicle for various WIM arrangements.

Road Roughness

The simulations have shown that roughness variation, even within good payments (PSI > 3.0), have a marked influence on the response. The results for the rough, medium, and smooth profile (PSI = 3.0, 3.4, and 3.8, respectively) show a distinct reduction in the response variation.

The general recommendation that WIM installations be used on pavements with PSIs greater than 3.0 can thus still lead to meaningful variations in dynamic responses. Once again the specific response will differ for each vehicle configuration. Some vehicles will react best on one pavement but will not be suitable on another.

Weigh-in-Motion Equipment Arrangement

The study has shown that the lead in profile and placement of the WIM equipment has a great influence on the response of a vehicle. This influence is however compensated by the calibration of the equipment.

The response of a vehicle at a specific point is also influenced by the roughness of the lead-in and exit road section. The placement of any system would thus require consideration of the general site condition at a potential installation point. In this regard the study by Cunagin et al. (*8*) suggests that a 150-m lead-in and a 30-m exit section need to be considered.

The results show that the vehicle dynamics, and thus the WIM results, could be different between two profiles with identical PSIs. This difference is because vehicle response is a combination of profile frequency and amplitude, as well as vehicle configuration, mass distribution, and suspension characteristics. The combinations are therefore limitless. The results also emphasize that even with good calibration, there will be a significant fluctuation in the errors obtained with WIM. Users therefore should be made aware of the potential accuracy of WIM measurements.

RECOMMENDATIONS

Similar to findings reported by Purdhoe (*4*) it is recommended that a range of vehicles be used to verify the weighing system. Furthermore, calibration factors should be determined for various vehicle configurations so as to limit the variation between the static and WIM results.

The use of a flush WIM arrangement is recommended to supply road loads. As suggested previously (*2*), the WIM systems currently available are not suitable for law enforcement purposes but rather should be used for vehicle screening. It has also been stated (*9*) that the WIM technology can provide reliable trend data to indicate where and when enforcement efforts may be needed.

The purpose of calibration has not yet been refined, and more work is needed to ensure reliable and consistent results at different sites and for various vehicles. The calibration curves must be set up to allow for all the various vehicle configurations that will be operating at the particular installation site.

As shown with the comparison of field (*3*) and simulation results it is suggested that vehicle simulation techniques be used to identify suitable WIM sites. The further calibration and installation should then be done for the WIM equipment at these identified sites.

REFERENCES

1. Petropola, T., G. Wass, R. Marshall, T. Neukam, D. Bochenek, D. Taylor, and E. Biggs. *Joint Pennsylvania/Maryland Weigh-in-Motion Demonstration Project*. Report Interstate 83. PennDOT/MD SHA/FHWA. Aug. 1991.
2. Slavik, M. M., and A. T. Visser. Development of a Weigh-in-Motion Network in South Africa. In *Transportation Research Record 1272*, TRB, National Research Council, Washington, D.C., 1990.

3. Viljoen, A. W., and F. C. Rust. *Interim Results of the Dynamic Axle Load Study Conducted at Boekenhoutkloof.* Technical Note TP/30/87. National Institute for Transport and Road Research, CSIR, Pretoria, South Africa, April 1987.
4. Purdhoe, J. *Slow Speed "Dynamic" Axle Weighers: Effects of Surface Irregularities.* Research Report 134. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1988.
5. Van Niekerk, P. E., and A. T. Visser. *Dynamic Effects of Heavy Vehicles on Road Pavements.* RDAC PR91/280. South African Roads Board, Pretoria, March 1992.
6. Fernando, E. G., R. L. Lytton, W. L. McFarland, J. L. Memmott, F. Helin, and A. N. Jamy. *The Florida Comprehensive Pavement Analysis System.* Florida DOT State Project 99000-172. Texas Transportation Institute, Texas A&M University, College Station, April 1991.
7. Visser, A. T. *A Correlation Study of Roughness Measurements with an Index Obtained from a Road Profile Measured with a Rod and Level.* Technical Report No RC/2/82. National Institute for Transport and Road Research, CSIR, Pretoria, South Africa, March 1982.
8. Cunagin, W. D., S. O. Majdi, and H. Y. Yeom. Intelligent Weigh-in-Motion Systems. In *Transportation Research Record 1311,* TRB, National Research Council, Washington, D.C., 1991, pp. 88–91.
9. Basson, J. E. B., A. T. Visser, and C. R. Freeme. In-Motion Weighing of Vehicles on Heavily Trafficked Roads. In *Transportation Research Record 1200,* TRB, National Research Council, Washington, D.C., 1988.

Publication of this paper sponsored by Committee on Vehicle Counting, Classification, and Weigh-in-Motion Systems.