# Rational Look at Truck Axle Weight

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The load applied by trucks on pavement varies instantaneously due to road roughness, truck speed, suspension type, tire pressure, and other factors. The instantaneous actual (dynamic) load fluctuates above and below the static weight, and the difference can be significant. Current weigh-in-motion (WIM) devices provide a snapshot of the dynamic load spectrum. These measurements can be improved by using multisensor devices to better represent the actual wheel load distribution. The larger the number of sensors in a WIM device, the larger the accuracy in representing the dynamic load spectrum. Multisensor WIM devices can be used to estimate both the mean and the standard deviation of the dynamic wheel forces applied by the tires on the pavement. A larger number of sensors is required to accurately estimate the standard deviation than the number required to accurately estimate the mean. Also, the chance of underestimating the actual standard deviation is larger than that of overestimating the actual standard deviation. Because pavement performance is affected more by dynamic loads than by static loads, dynamic loads could be better used to control the legal load limit, taxation, penalties, and pavement design and analysis. Further research is needed to provide proper implementation procedures and to separate the dynamic forces caused by truck and road factors.

The pavement design process requires a large amount of input data, including traffic characteristics, material properties, and environmental conditions. The crux of the problem is how to analyze these data to determine optimum layer thicknesses so that the pavement will last for a specified design life without excessive failure. One of the important areas of analysis is to evaluate how the pavement is affected by the application of wheel loads under various conditions—a problem that has not been fully resolved.

The load applied by trucks on the pavement structure is dynamic, which means that it varies from one instant of time to another, as shown in Figure 1 (*1*). Figure 1 shows that the instantaneous wheel force of a walking beam suspension truck, for example, could vary from 25 to 175 percent of the static wheel load at a speed of 50 mph on a medium-roughness road. Other studies (*2,3*) show that the dynamic forces applied by moving truck wheels have typical root mean square amplitudes of 10 to 30 percent of the static wheel loads. The fluctuation of the dynamic wheel load above and below the static weight is affected by road roughness, truck speed, suspension type, tire type, tire pressure, tire condition (bald or new), load center of gravity, and frame and axle configuration. For example, two axles having the same static weight but different suspension types, tire types, tire pressures, speeds, or pavement roughness will affect the pavement differently.

Forces on the pavement applied by vehicles in motion have a different character than those produced by stationary vehicles. The interaction between moving vehicles and pavement is a complex process that has not been fully understood or addressed either by highway engineers or by vehicle manufacturers.

The conventional practice of weighing trucks is to obtain the static weights of various axles. This static axle load is currently being used for pavement analysis and design, truck taxation and fining, fund allocation for road maintenance, and pavement management. In recent years the weigh-in-motion (WIM) technique has been used by most states in an attempt to obtain axle weights in a more comprehensive, simpler, and faster way than the static technique. However, there is a great concern among highway engineers because the WIM devices do not duplicate the static weight. Also, under the same conditions the same WIM device does not even record the same weight; thus, the results are not repeatable.

Results of recent research related to vehicle-pavement interaction are reviewed, and some issues crucial to the pavement and truck community are discussed. A new, accurate, and precise concept of how truck axles could be weighed and analyzed is proposed. The justification and potential use of the new method of axle weighing in pavement design, road maintenance, budget allocation, and truck taxation are addressed.

## DYNAMIC MOVEMENTS OF TRUCKS

The characteristics of heavy vehicles that are of greatest interest to pavement performance include suspension and axle configuration, tire type and pressure, axle load, and vehicle speed. These vehicle characteristics have significantly changed since the AASHO road test, which developed the relationship between truck traffic and pavement wear and formed the basis for the pavement design and truck weight regulations currently used in many states. These changes in heavy-vehicle characteristics made the current methods of pavement design obsolete or biased. The main reason for this problem is the empirical nature of these design methods, which are valid only under the original conditions and are not accurately adaptable to changes in these conditions.

A heavy truck is complex from the standpoint of dynamics. The mass of the truck can be broken down into a sprung mass and an unsprung mass (*4*). The sprung mass includes body, frame, powertrain, payload, and driver. The unsprung mass includes axles, spindles, brakes, wheels, and tires. Both sprung and unsprung masses bounce and contribute independently to the composite dynamic pavement load, although the bouncing of the sprung mass is much greater than that of the unsprung mass. The total load imparted to the pavement by a

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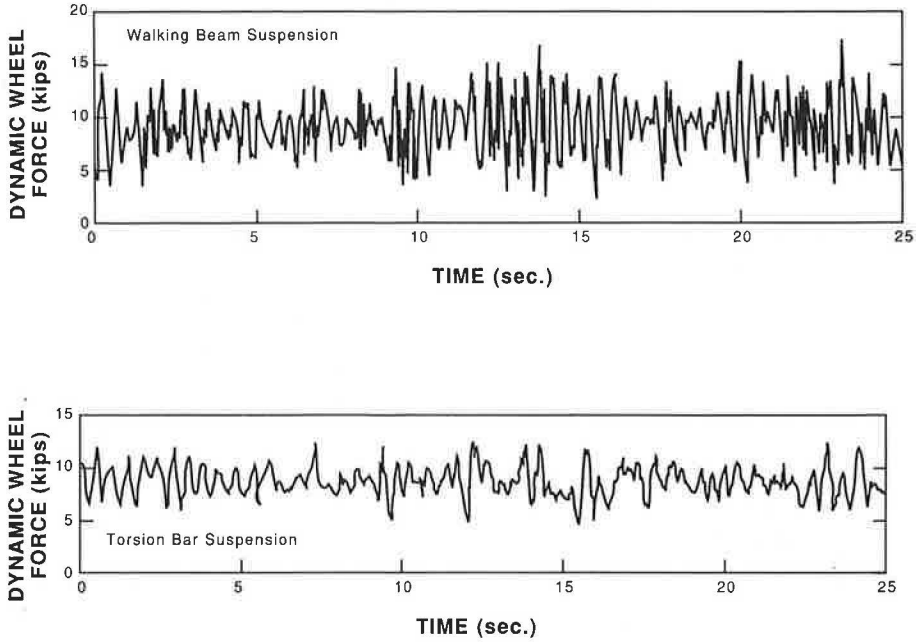


**FIGURE 1 Typical instantaneous dynamic wheel force at 50-mph speed for medium road roughness (*1*).**

moving vehicle is the sum of the static load or weight of the vehicle and the forces generated by the vertical movements of both sprung and unsprung masses. The force generated on the pavement is related to the vertical movement according to Newton's second law (force = mass × acceleration). Additional impact forces are also generated when tires lose pavement contact.

Figure 2 shows various movements of the sprung and unsprung masses of the truck. The sprung (suspended) mass develops three types of motion: bounce, pitch, and roll. The bounce is a simple up-and-down motion of the entire mass, whereas the pitch is an out-of-phase fore-and-aft bounce. The roll, which is relatively small, is an out-of-phase side-to-side bounce. In general, these motions are coupled, and an impulse at the front or rear wheels excites them. The motions occur at the natural frequency of the system, which is the frequency with which the system oscillates in the absence of external forces. The natural frequency of bounce oscillation for a heavy-duty vehicle at rated loads is about 1 to 2 Hz, whereas body pitch typically occurs at 6 to 7 Hz. These natural frequencies increase as the suspended mass is reduced by payload removal (*4*).

The unsprung mass also exhibits oscillatory behavior, but at a natural frequency that is somewhat higher than that of the sprung mass. In the case of a single axle suspension, two types of motion occur. The axle may bounce up and down, with its centerline parallel to the ground, or the axle ends may bounce out of phase with each other (tramp). In the case of a tandem axle suspension, a third vibration mode of interaxle pitch is possible. In this mode, the tire force is cyclically shifted fore and aft between the two axles. The presence of this interaxle pitch requires a coupling mechanism between the two axles. The natural frequency of axle bounce and interaxle pitching is in the range of 10 to 12 Hz. The extent to which these interaxle vibration modes predominate, or exist at all, is a function of the design of the suspension system (*4*).

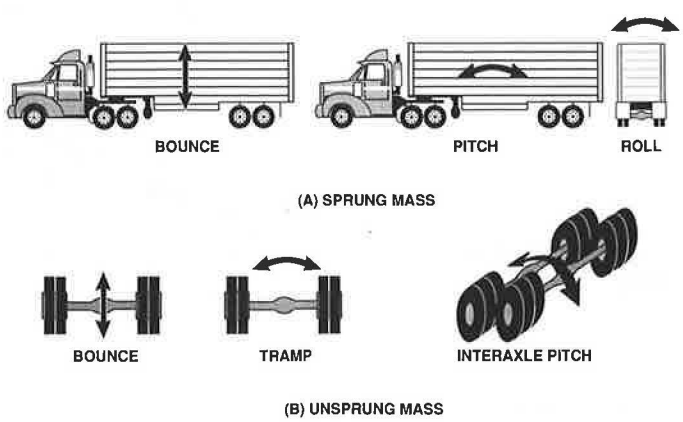


**FIGURE 2 Movements of the sprung and unsprung masses.**

## SUSPENSION CHARACTERISTICS AND TYPES

The suspension is the mechanical system by which the axles of a truck or trailer are mounted on the vehicle chassis. The suspension is designed to achieve optimum load-carrying capacity, durability, stability and control, and ride quality, under service conditions that are determined by overall vehicle design, drive train and tire characteristics, cargo and operational usage, and road conditions (*5*). These design objectives are not necessarily optimum conditions for road performance. The following paragraphs discuss specific properties and types of suspension systems.

The suspension system consists essentially of a spring mechanism and a damping system. The springs are components of the suspension intended to absorb the energy of the vehicles' bumping over road surface irregularities. Several types of springs are used in truck suspensions. Steel leaf springs and air bags are the most popular. Flexible beams, torsion bars, and rubber and rubber-steel composite blocks are other common types. On the other hand, the damping system may include shock absorbers or other devices designed to dissipate (damp) the bouncing vibrations of the vehicle and springs, as well as rods, bars, or beams intended to transfer loads between adjacent axles and to stabilize the truck and trailer. Load transfer and dynamic behavior (vibrations and damping) are key to how axle suspensions influence pavement wear. These components work with the springs to give a suspension the operating qualities that make it suitable for particular uses.

A number of approaches have been developed over the years for meeting the diverse performance requirements of tandem and triaxle suspensions of heavy-duty trucks. These approaches can be grouped into four design categories that are representative of virtually all current production: the walking beam, the leaf spring, the air suspension, and the torsion bar. Different suspensions affect pavement performance differently, according to the way the load is transmitted to the truck axles. Also, the same suspension type can affect the pavement differently depending on whether it is a prime mover (tractor) suspension or a trailer suspension. This difference is caused by the tractive force produced between the tires of the tractor suspension and the pavement surface, which can transfer part of the load from one axle to the other. The following paragraphs summarize the main features of various suspension types and how they affect pavement (*4*).

### Walking Beam Suspension

The walking beam suspension, shown in Figure 3a, is favored for its roll resistance, off-road performance, and equalization effectiveness and comprises a large, though diminishing, portion of the overall tandem suspension population. The dynamic pavement loading activity of the walking beam can be described as moderate to high over smooth and slightly rough roads and high over very rough roads. The walking beam suspension exhibits the largest dynamic loading of the four suspension types. Because there is so little damping at the walking beam, oscillation amplitudes can become high if road inputs are encountered at the natural frequency of interaxle pitch.

### Leaf Spring Suspension (Four- and Six-Spring)

The leaf spring suspension is the most common heavy-duty suspension for on-highway vehicles, primarily due to its low cost, low weight, and low maintenance requirements (see Figure 3b). These features make the leaf spring particularly popular for use on trailers and converter dollies. For the most part, the behavior of the leaf spring is indicative of the behavior of any single-leaf suspension, such as that used almost universally as the front-axle suspension of heavy-duty vehicles.

The dynamic pavement loading activity of the leaf spring suspension can be described as moderate over most roads and is generally acknowledged to represent an improvement over the activity level of the walking beam suspension. The leaf spring suspension was the type used in the AASHO road test.

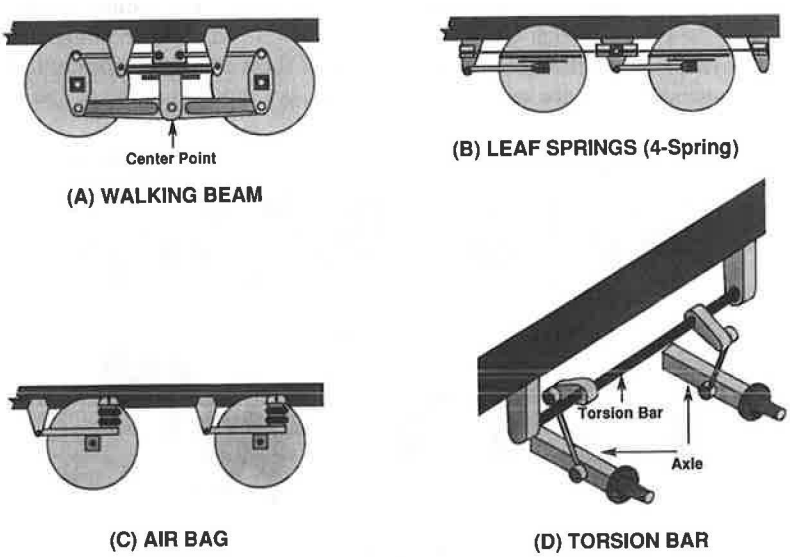


**FIGURE 3 Common suspension types.**

### Air Suspension (Air Bag)

Although the air suspension, shown in Figure 3c, is often more expensive than the other suspension types, it has become increasingly popular in recent years because of its smooth ride and the protection afforded the cargo. The air suspension generally exhibits the least amount of dynamic loading activity of the four suspension types.

### Torsion-Bar Suspension

The torsion-bar suspension, shown in Figure 3d, is used primarily in the western United States and Australia. Typically priced slightly higher than the four spring, the lightweight torsion-bar suspension generally provides the best ride offered by a mechanical suspension. However, it is not commonly used, principally because of its frequent lubrication requirements and high rebuild cost. Dynamic activity of the torsion bar is low to moderate and is generally acknowledged to be considerably lower than that of the four spring.

The percent shares of various suspension types on new trucks in the United States are presented in Table 1 (*5*).

## TIRE TYPES AND PRESSURE

The tires used in the AASHO road test were predominately bias ply inflated to 75 to 80 psi cold inflation pressure, which was the standard practice and manufacturer's specification at the time. Currently, radial tires are common on heavy trucks, with typical pressures of 100 psi. Also, new tire designs, such as low-profile tires and wide-base single tires to replace dual tires, are gaining acceptance.

Tires are constructed with several layers of rubber and fiber. Older designs used natural or synthetic fiber cord wrapped on an angle with respect to the tire tread (i.e., on the bias). In radial tires, the ply is wrapped perpendicular to the tread direction. Both bias and radial tires may be reinforced with fiber belts of steel, glass, or other material wrapped generally parallel with the tread direction. Bias-ply tires accounted for almost the entire U.S. tire market until the 1970s, when European experience with improved wear, fuel economy, and road hazard resistance of radial tires began to have an impact (*6*).

A rapidly growing share of the tire market for long-haul highway trucks is being met by the newer low-profile tires, which have smaller diameters than regular tires. The main advantage of low-profile tires may be the reduction in vehicle height and the associated increase in trailer cubic capacity.

TABLE 1 PERCENT SHARES OF VARIOUS SUSPENSION TYPES ON NEW TRUCKS IN THE UNITED STATES

| Suspension Type | Tractors | Trailers |
|---|---|---|
| Walking Beam | 15-25 | <2 |
| Leaf Spring | 55-70 | >80 |
| Air Bag | 15-20 | 10-15 |
| Other | 2-4 | Nil |

Some manufacturers have introduced single wide-base tires (super singles) to be used in place of dual tires or when higher loads are to be carried. The main advantage of wide-base tires is the improved fuel economy. Most wide-base tires in the United States are used on front drive axles of heavy hauler vehicles.

Tire inflation pressures maintain the tire's design profile and thus proper road contact under vehicle loading. Vehicle operations with improper tire pressures lead to excessive tire wear, particularly with radial tires, and influence vehicle handling characteristics. Too low a pressure at a particular load causes the tire to flatten out more and, in turn, causes added flexure and heat buildup in operation. Too high a pressure reduces contact area and stiffens the tire, increasing the risk of skidding and loss of breaking ability.

Higher tire pressure produces greater stress at the surface of the pavement, and highway engineers suspect that this effect is sometimes implicated in problems with wheelpath rutting on flexible pavement. Other characteristics of tires also influence the distribution of forces under the tires and, thus, may affect pavement wear.

## VEHICLE-PAVEMENT INTERACTION

Knowledge of the interaction between trucks and roads is insufficient to provide the clear understanding needed to develop a completely mechanistic pavement design method. Over the years, the trucking community has supported basic research leading to the development of mechanistic models for truck dynamic behavior. Although much of this effort has focused on handling a braking behavior, the models provide a foundation for prediction of pavement loading produced by trucks (*7*).

Current mechanistic practice for pavement analysis and design oversimplifies the vehicle-pavement interaction process. In general, a constant-magnitude static wheel load is imposed on a multilayered elastic pavement system, and such critical responses as stresses and strains are computed. These critical responses are further related to pavement life using some empirical relations. Although this method of pavement analysis and design is much more sophisticated than purely empirical design approaches, the vehicle-pavement relationship is still considered a one-way relationship in which vehicles affect pavement but pavement does not affect vehicles.

Pavements and vehicles impose forces on each other through a process of progressive deterioration of the pavement surface because of applied loads. This pavement deterioration leads to excitation of axle suspensions and results in greater dynamic loads on the pavement surface. The process, therefore, is an accelerating one in which variations in pavement condition and vehicle load reinforce each other through time, becoming more significant as the pavement deteriorates further. Because this reciprocal imposition of forces is influenced both by pavement characteristics and by vehicle characteristics, both of these factors must be considered in a dynamic, or time-dependent, environment, along with other contributing factors, such as vehicle speed, in predicting the accumulation of pavement damage. The implication of this interactive process is that preservation of highway infrastructure can be managed not only through changes in pavement design, construc-

tion, maintenance, rehabilitation, and reconstruction, but also through control of vehicle dynamic loads by improving the characteristics of vehicles (*8*).

The study of vehicle-pavement interaction requires the following basic elements (*7*):

1. A mechanistic truck dynamic model that computes the dynamic vehicle loads applied on the pavement as a function of pavement roughness and vehicle characteristics.
2. A mechanistic pavement dynamic model that computes the dynamic pavement responses as a function of the dynamic vehicle loads and pavement geometric and material properties; and
3. A pavement deterioration model that relates the pavement responses to pavement damage.

The process can be simplified by developing a truck equivalency formula, which combines various truck properties that, in turn, can be related to pavement damage by an equivalent damage formula. Currently, an NCHRP project (*9*) is being performed to investigate these issues.

The term "dynamic load" indicates variable loading with time. A true dynamic model should also consider the inertia of the object. This principle can be applied to vehicles as well as to the pavement structure. In other words, there is a difference between the dynamic modeling of vehicles and that of pavements. A dynamic vehicle model could be used with a static pavement model or vice versa. An accurate analysis of the effect of vehicles on pavement should consider the dynamic response both of vehicles and of pavement as well as their interactions, such a model does not currently exist.

## EFFECT OF ROUGHNESS, SPEED, AND TIRE PRESSURE ON DYNAMIC FORCE FOR VARIOUS SUSPENSIONS

A limited number of studies (*1,4,10,11*) have been performed to evaluate the dynamic force generated by various suspension types on the pavement surface. Two approaches can be used to measure the wheel dynamic force. The first approach is to attach sensors to the pavement surface in the wheelpath and to measure the actual load applied on the pavement. The shortcoming of this approach, however, is that the wheel force varies from one instant to another. Therefore, each pavement sensor does not provide a good representation of the variable load applied on the pavement surface but records a snapshot of the wheel load spectrum. The second approach for measuring the wheel dynamic force is to attach sensors to the truck axles. Although the latter method provides continuous recording of the dynamic force applied on the axle, the force is not the exact same force that is applied on the pavement surface. The difference between the axle force and the pavement force is a function of the stiffness of the tires, which introduces yet another element of dynamic load measurement variability.

A study to evaluate dynamic pavement loading characteristics was conducted by Sweatman (*1*). The study was sponsored by the Australian Road Research Board in response to a recommendation by the National Association of Australian State Road Authorities (NAASRA). In the study, a wheel force transducer was used to measure dynamic wheel loads in two- and three-axle groups for speeds ranging between 25 and 50 mph over road surfaces ranging from as-new construction to those exceeding the maximum desirable tolerable roughness. The effects of tire inflation pressure and axle group load were taken into account. All tires used in the study were tubeless, radial dual tires. A factorial experimental design was used to determine the dynamic loading expressed as a form of coefficient of variation, termed the "dynamic load coefficient" (DLC). Nine suspension types were tested, including five tandem drive axle suspensions and four trailer suspensions (two tandem groups and two triaxle groups). In addition to the DLC, the load-sharing performance of each suspension (or how uniformly the load is shared by various axles within the suspension group) was examined. Two replicate tests were performed for each factor combination.

In Sweatman's study (*1*), roughness was measured by the NAASRA roughness meter (*12*), which operates by summing positive rear-axle-to-body displacements in a standard station sedan traversing the road at traffic speed. Roughness is expressed in arbitrary units of counts per kilometer (or counts per mile).

Data extracted from the Sweatman study (*1*) were reanalyzed and plotted in Figures 4–7 to show the effect of road roughness, vehicle speed, and tire pressure on the dynamic force for various suspension types. The four figures show the response of a walking beam drive tandem axle, a leaf spring trailer axle, an air bag trailer tandem axle, and a torsion-bar drive tandem axle, respectively. The dynamic force on the pavement surface is expressed in terms of the DLC. The DLC is defined as the standard deviation of the wheel force distribution divided by the overall mean wheel force. Of course, the larger the variability of the dynamic force applied on the pavement, the larger the DLC.

As shown in the figures, the variability of the wheel force (DLC) increases with increasing road roughness and truck speed. However, changing the tire pressure from 70 to 100 psi did not significantly change the DLC value in most cases. A comparison of the four figures shows that the walking beam suspension has the largest dynamic load effect of the suspension types.

## WEIGH-IN-MOTION

There are many variations of products on the market for weighing of highway vehicles in motion, offered by as many as 10 different vendors. Current technologies include strain gauge load cells, strain gauges on a beam, strain gauge bending plates, capacitance pads, capacitance strips and piezoelectric cables and films. Each of these is currently being tested or is in actual use; as of 1988, 46 states had or have had WIM systems. The technology has been developed for more than 40 years in the United States, and enhancements will probably continue for many years.

A great concern indicated by various highway agencies is that the WIM devices are not accurate enough because they do not duplicate the static weight (*13–15*). Also, the devices do not record the same weight under the same conditions; thus, the results are not repeatable.

According to the previous discussion on vehicle dynamics, the problem is not the accuracy of the WIM devices but, rather, how to interpret the WIM results. When a truck wheel

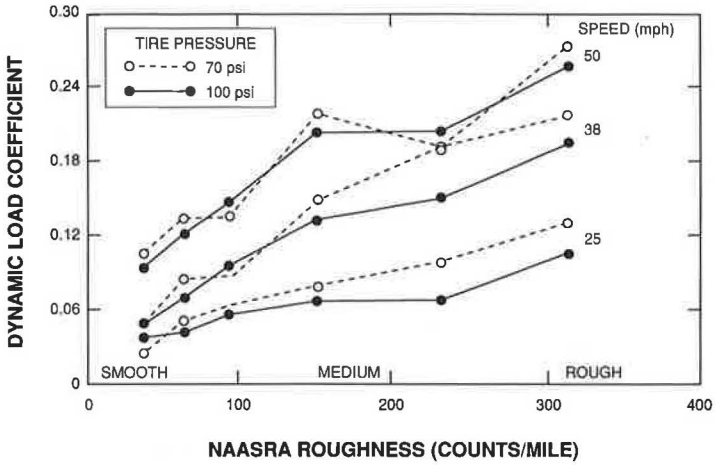


**FIGURE 4 Effect of roughness, speed, and tire pressure on the dynamic load coefficient of walking beam suspension (*1*).**

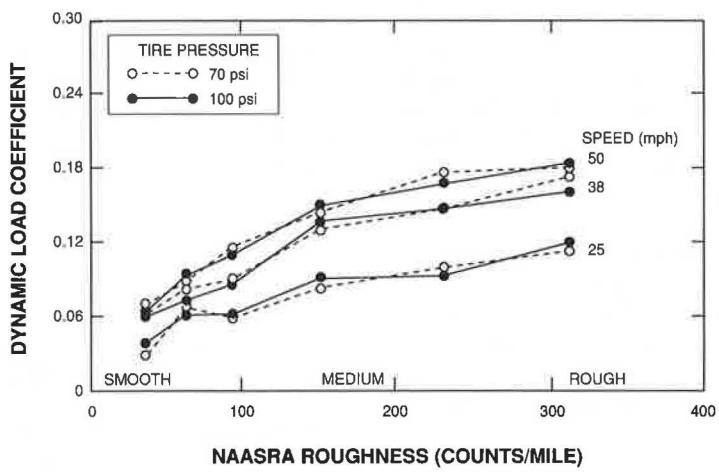


**FIGURE 5 Effect of roughness, speed, and tire pressure on the dynamic load coefficient of leaf spring suspension (*1*).**

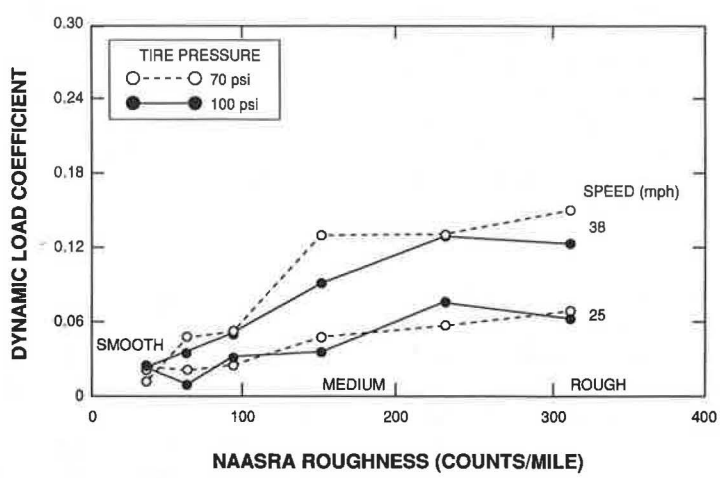


**FIGURE 6 Effect of roughness, speed, and tire pressure on the dynamic load coefficient of air bag suspension (*1*).**

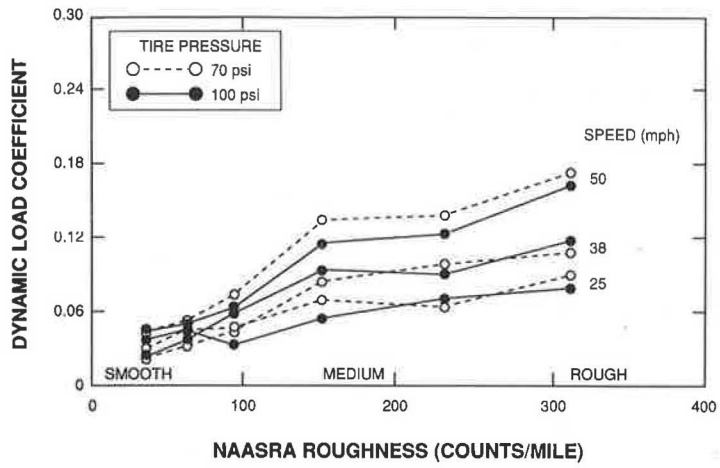


**FIGURE 7 Effect of roughness, speed, and tire pressure on the dynamic load coefficient of torsion-bar suspension (*1*).**

passes over any point on the pavement surface, this point feels a certain instantaneous dynamic force. Because the dynamic force applied by the truck wheel on the pavement surface varies instantaneously above and below the static weight, it would be a coincidence if the constant static and the variable dynamic readings matched. Therefore, the WIM device records the actual dynamic force that is applied at that instant of time, which is generally different than the static weight. This instantaneous force could be at the peak, at the lowest point, or at any point in between.

Of course, there could be some device errors, as with any other device. However, it is believed that most of the inconsistencies in results obtained by WIM devices are due to the dynamic effect. Thus, the difference between the WIM results and the static weight should not be viewed as error or inaccuracy but, rather, as the difference between dynamic and static effects.

## MULTISENSOR WIM DEVICE

In order to measure the dynamic weight or to estimate the static weight from the dynamic weight, a multisensor device can be used rather than a single-sensor device. These sensors will obviously record different weights for the same moving wheel. If the number of these sensors is large enough, the average value of various sensor readings will usually give a good estimate of the static wheel weight. Also, the variance of various sensor readings will provide a good estimate of the variance of the dynamic forces. However, some deviations might result due to the effect of traction forces between tires and pavement and due to the effect of the geometry of the truck frame.

Glover (*16*) performed numerical simulation of multisensor WIM outputs with a variety of spacing arrangements. He concluded that a WIM System with nine evenly spaced sensors could yield a good estimate of the static load. Cebon (*17*) performed theoretical analysis and concluded that a WIM device with three evenly spaced sensors could provide a reasonable estimate of the static load. He indicated that the average value of the three sensor outputs provides reasonable accuracy for a wide range of speeds an dynamic loading frequencies. With such an arrangement, the theoretical coefficient of variation of the difference between static and dynamic weights can be reduced to 30 to 50 percent of the difference for a single-sensor WIM system. On the basis of the Cebon study (*17*), a portable WIM pad with three equally spaced capacitive strip transducers is being developed by Golden River Ltd. in the United Kingdom (*18*).

## A NEW MULTISENSOR WIM APPROACH

Up to the present time, the objective of highway engineers has been obtaining an accurate static axle or wheel weight. This static weight is currently being used to enforce the legal load limit and to provide a basis for pavement analysis, truck taxation, penalty, and other truck regulations. Even the multisensor WIM concept proposed by Glover (*16*) and Cebon (*17*) is based on improving the WIM results to get values close to the static weight.

It should be realized, however, that the pavement does not "feel" the static weight of moving wheels but, rather, the instantaneous dynamic force. Thus, the rate of pavement deterioration is more correlated to the dynamic weight than the static weight. For example, two axles having the same static weight but different speeds or different suspension types, or driven on pavements with different roughnesses, will affect the pavement differently. The difference in effect increases with increasing truck speed and pavement roughness and varies with suspension type.

A new approach is suggested in which a multisensor WIM device is used to capture the dynamic force distribution generated by the truck wheel rather than averaging the dynamic readings to estimate the static weight. Also, the legal load limit, taxation, and penalties, as well as pavement design and analysis, could be a function of the dynamic wheel forces actually applied on the pavement rather than the static weight.

One of the difficulties of this new approach, however, is the separation between the dynamic effect caused by the truck due to such factors as the truck's static weight, suspension type, speed, and tire pressure and the dynamic effect caused

by the road roughness. Although pavement design, equivalency factors, and pavement performance analysis should consider both truck and pavement factors, truck taxation and penalties should be based on truck factors only. For example, truck companies cannot be penalized if the highway agency does not properly maintain the road. One possible solution to this problem is to develop adjustment factors for different road roughnesses and to base the truck taxation and penalties on a standard or typical pavement roughness.

To obtain the optimum number of sensors in a multisensor WIM device, statistical analysis of dynamic loading data could be performed. The objective of the statistical analysis is to compute the number of sensors required in a multisensor device to represent the dynamic wheel forces within a specified tolerable error with a reasonable confidence level. Of course, the larger the number of sensors, the more closely the dynamic forces can be represented. In other words, the larger the sample size, the more the population can be represented. On the other hand, the larger the number of sensors, the more expensive the WIM device.

Two statistical approaches can be used to compute the minimum number of sensors needed in a WIM device to represent various dynamic forces accurately. The first approach is to limit the maximum error in estimating the mean of the dynamic forces, whereas the second approach is to limit the maximum error in estimating the standard deviation of the dynamic forces. If the objective is to accurately estimate the static weight from the dynamic forces, only the first approach is needed. However, if the objective is to accurately represent various dynamic activities of the truck, both approaches are needed.

In this analysis, the dynamic forces of the truck are assumed to be normally distributed. In order to estimate the maximum amount of error in predicting the mean of the dynamic forces that corresponds to a certain number of WIM sensors, the following inequality can be used:

$$-\frac{sz_\alpha}{n^{1/2}} \leq \mu - \bar{x} \leq +\frac{sz_\alpha}{n^{1/2}} \tag{1}$$

where

$\mu$ = mean of the population of the dynamic forces (actual mean);
$\bar{x}$ = mean of the sample of the dynamic forces (estimated mean);
$s$ = standard deviation of the sample of the dynamic forces (estimated standard deviation);
$n$ = sample size (number of WIM sensors);
$z_\alpha$ = standardized normal deviate, which is a function of the desired confidence level; and
$100\ (1 - \alpha)$ = confidence level.

To estimate the maximum amount of error in predicting the standard deviation of the dynamic forces that corresponds to a certain number of WIM sensors, it can be assumed that the term $(n - 1)s^2/\sigma^2$ follows a $X^2$ distribution with $(n - 1)$ degrees of freedom. It follows that

$$s\left[\frac{(n-1)}{X_U^2}\right]^{1/2} \leq \sigma \leq s\left[\frac{(n-1)}{X_L^2}\right]^{1/2} \tag{2}$$

which implies that the ratio $\sigma/s$ can be estimated as follows:

$$\left[\frac{(n-1)}{X_U^2}\right]^{1/2} \leq \frac{\sigma}{s} \leq \left[\frac{(n-1)}{X_L^2}\right]^{1/2} \tag{3}$$

where

$\sigma$ = standard deviation of the population of the dynamic forces (actual standard deviation) and
$X_U^2$ and $X_L^2$ = upper and lower percentage points of the $X^2$ distribution, respectively, which are functions of the desired confidence level and degrees of freedom $(n - 1)$.

Data reported by Sweatman (*1*) have been used to estimate the optimum number of WIM sensors. Sweatman measured the dynamic wheel forces for different suspension types, truck speeds, tire pressures, and road roughnesses but did not explicitly report the means and standard deviations of various dynamic forces. Instead, two data parameters are reported: the DLC and the load sharing coefficient (LSC). The LSC was obtained by dividing the mean value for each wheel force distribution by the static wheel load (assuming equal load distribution between the wheels in the group). Thus, the LSC indicates the variations between the measured mean wheel force and its expected or desired value and is given by the following (*1*):

$$\text{LSC} = \frac{2n\bar{x}}{Mg} \tag{4}$$

where

$n$ = number of axles in the group,
$\bar{x}$ = mean wheel force,
$M$ = axle group mass, and
$g$ = gravitational acceleration.

Using the LSC data reported by Sweatman (*1*), the mean wheel forces were computed according to Equation 4. Furthermore, the DLC is given by the following:

$$\text{DLC} = \frac{s}{\bar{X}} \tag{5}$$

where

$s$ = standard deviation of the wheel force distribution and
$\bar{X}$ = overall mean wheel force (average of $\bar{x}$).

Equation 5 was used to compute the standard deviation of the dynamic wheel forces from the DLC and the overall mean wheel force ($\bar{X}$) values obtained in Equation 4.

Although data are provided by Sweatman (*1*) for both tandem and tridem axles, only tandem axles were used in the present study. Using Equation 1, the error in estimating the mean of the dynamic wheel forces associated with different numbers of WIM sensors was computed for four tandem-axle suspension types. Table 2 presents the error in estimating the means of the dynamic wheel loads for various numbers of sensors for 100-psi tire pressure at 95 percent confidence level. Figures 8–11 show the same results graphically for the walking

TABLE 2 MAXIMUM ERROR IN ESTIMATING THE MEAN OF THE DYNAMIC WHEEL LOAD FOR VARIOUS NUMBERS OF SENSORS FOR 100-psi TIRE PRESSURE AT 95 PERCENT CONFIDENCE LEVEL

| SUSPENSION | ROUGHNESS* | SPEED (MPH) | ERROR(KIPS) FOR NO. OF SENSORS ** | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1 | 3 | 5 | 7 | 9 |
| WALKING BEAM | Low | 25 | 0.5 | 0.3 | 0.2 | 0.2 | 0.2 |
| | | 50 | 1.2 | 0.7 | 0.6 | 0.5 | 0.4 |
| | High | 25 | 1.4 | 0.8 | 0.6 | 0.5 | 0.5 |
| | | 50 | 3.4 | 1.9 | 1.5 | 1.3 | 1.1 |
| LEAF SPRING | Low | 25 | 0.5 | 0.3 | 0.2 | 0.2 | 0.2 |
| | | 50 | 0.9 | 0.5 | 0.4 | 0.3 | 0.3 |
| | High | 25 | 1.7 | 1.0 | 0.8 | 0.6 | 0.6 |
| | | 50 | 2.6 | 1.5 | 1.2 | 1.0 | 0.9 |
| AIR BAG | Low | 25 | 0.3 | 0.2 | 0.1 | 0.1 | 0.1 |
| | | 50 | – | – | – | – | – |
| | High | 25 | 0.9 | 0.5 | 0.4 | 0.3 | -.3 |
| | | 50 | – | – | – | – | – |
| TORSION BAR | Low | 25 | 0.6 | 0.3 | 0.3 | 0.2 | 0.2 |
| | | 50 | 0.7 | 0.4 | 0.3 | 0.3 | 0.2 |
| | High | 25 | 1.4 | 0.8 | 0.6 | 0.5 | 0.5 |
| | | 50 | 2.7 | 1.6 | 1.2 | 1.0 | 0.9 |

*Low and high correspond to NAASRA roughness meter readings of 35 and 312 counts/mile, respectively.

**All errors are positive or negative.

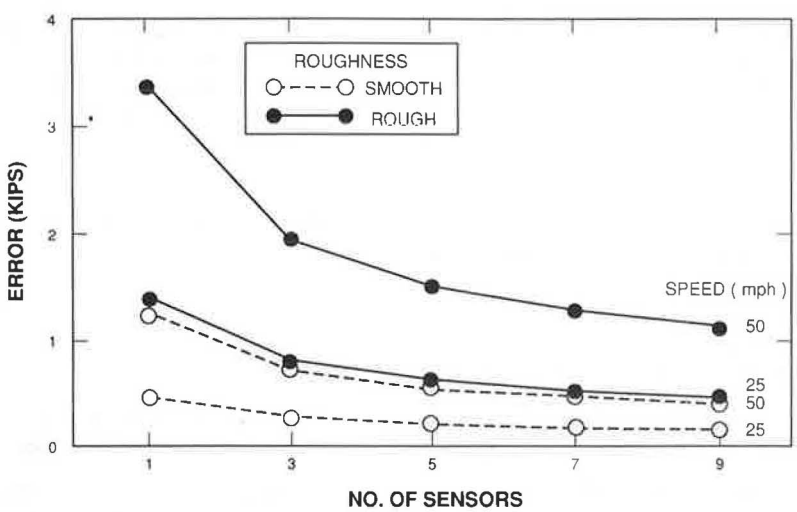


**FIGURE 8 Maximum error in estimating the mean of the dynamic wheel load for walking beam suspension for 100-psi tire pressure at 95 percent confidence level.**

beam, leaf spring, air bag, and torsion-bar suspensions, respectively.

Figures 8–11 show that the maximum error in estimating the mean of the dynamic wheel force decreases with an increase in the number of sensors. This conclusion is valid for various suspension types, roughnesses, and speeds. The largest reduction in error in estimating the mean of dynamic forces is obtained by increasing the number of sensors from one to three. Increasing the number of sensors more than three does not considerably reduce the error. For example, for the walking beam suspension, high roughness, and 50-mph speed, the maximum error for one, three, five, seven, and nine sensors decreases from ±3.4 to ±1.9 to ±1.5 to ±1.3 to ±1.1 kips, respectively.

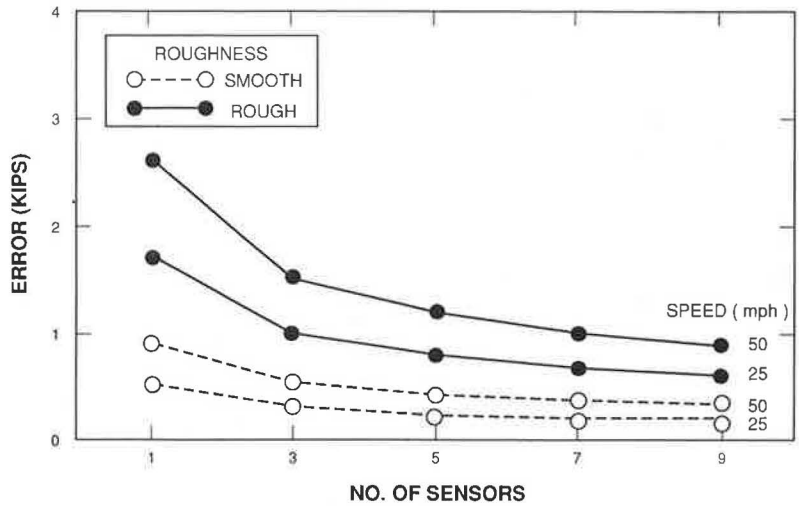


**FIGURE 9 Maximum error in estimating the mean of the dynamic wheel load for leaf spring suspension for 100-psi tire pressure at 95 percent confidence level.**

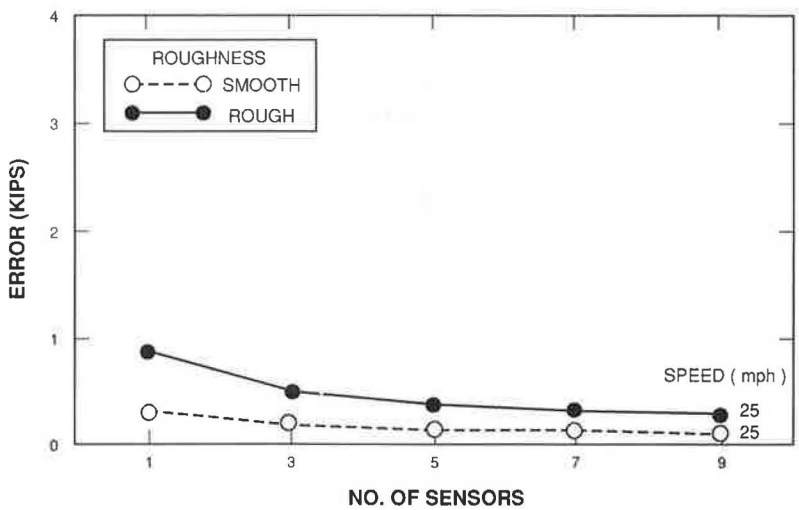


**FIGURE 10 Maximum error in estimating the mean of the dynamic wheel load for air bag suspension for 100-psi tire pressure at 95 percent confidence level.**

Figures 8–11 also show that the maximum error in estimating the mean of the dynamic wheel load using a specific number of sensors varies with roughness, speed, and suspension type. As expected, this error increases with increasing roughness or speed, or both. The air bag suspension results in the smallest maximum error even at high speeds because of its small dynamic movements.

Using Equation 3, the maximum and minimum ratios between the actual standard deviation ($\sigma$) and the measured standard deviation were completed for various numbers of sensors at a 95 percent confidence level, as presented in Table 3. The minimum and maximum ratios are not reciprocals. Also, these ratios are the same for different suspension types, roughnesses, and speeds because they are not affected by the actual means or standard deviations. Figure 12 shows the ratios between the actual and estimated standard deviations for various numbers of sensors at a confidence level of 95 percent.

In Table 3 and Figure 12, when the number of sensors in a WIM device increases, the actual and estimated (measured) standard deviations approach each other more closely. For example, when the number of sensors is three, the ratio between the actual and estimated standard deviations varies between 58 and 442 percent, whereas this ratio varies between 72 and 171 percent when the number of sensors is nine. However, increasing the number of sensors by more than five does not considerably reduce the error in estimating the standard deviation. Also, the upper limit of the actual and estimated standard deviations is farther than one from the lower limit. This difference indicates that, when using a specific number of sensors, the chance of underestimating the actual standard deviation is larger than the chance of overestimating the actual standard deviation.

Comparing Figure 12 with Figures 8–11, the errors in estimating the standard deviation are larger than the errors in estimating the mean for the same number of sensors. This

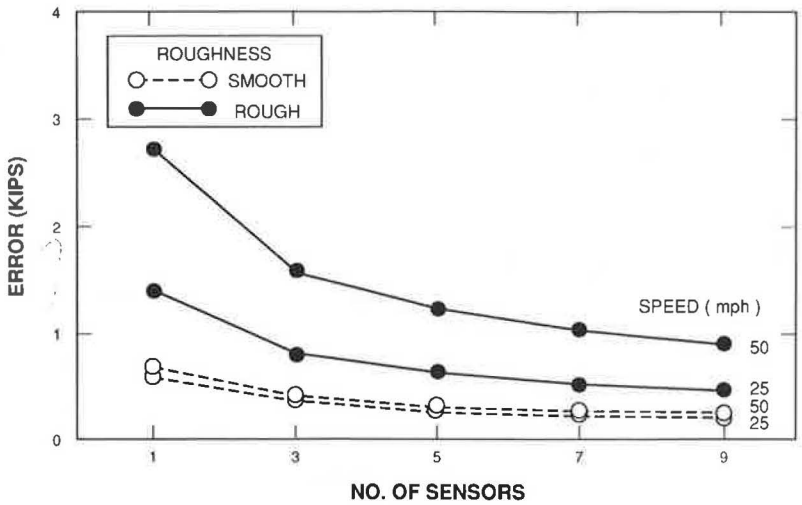


**FIGURE 11 Maximum error in estimating the mean of the dynamic wheel load for torsion-bar suspension for 100-psi tire pressure at 95 percent confidence level.**

TABLE 3 MAXIMUM ERROR IN ESTIMATING THE STANDARD DEVIATION OF THE DYNAMIC WHEEL LOAD AT 95 PERCENT CONFIDENCE LEVEL

| NO. OF SENSORS | ACTUAL/ESTIMATED STANDARD DEVIATIONS | |
|---|---|---|
| | MINIMUM | MAXIMUM |
| 1 | N/A* | N/A |
| 3 | 0.58 | 4.42 |
| 5 | 0.65 | 2.37 |
| 7 | 0.69 | 1.92 |
| 9 | 0.72 | 1.71 |

*N/A = not applicable

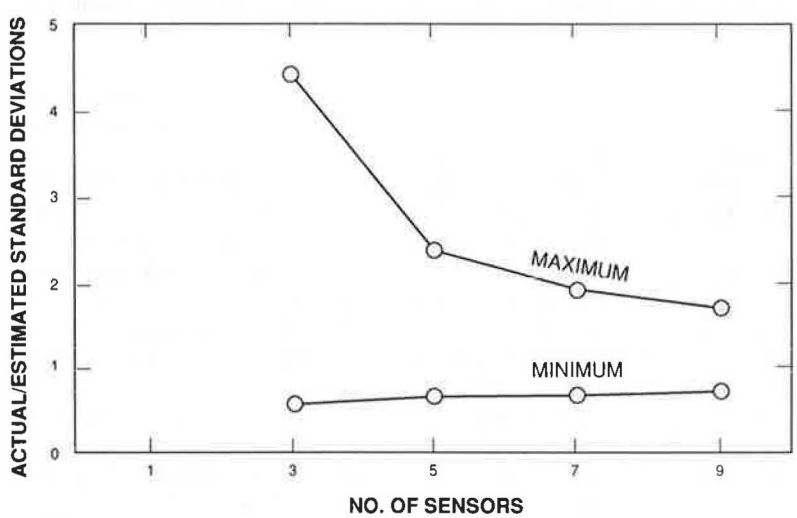


**FIGURE 12 Maximum error in estimating the standard deviation of the dynamic wheel load at 95 percent confidence level.**

finding means that a larger number of sensors is required in a WIM device to accurately estimate the standard deviation than the number required to accurately estimate the mean.

## WHEEL VERSUS AXLE DYNAMIC LOADS

The wheel load is defined here as a dual wheel on one side of an axle. All data reported have been for tandem axles. The extrapolation of the dynamic axle weight from the dynamic wheel weight is not straightforward due to the dynamic movements of the sprung and unsprung masses reported previously (see Figure 2). In cases with only vertical bounce of sprung and unsprung masses, the instantaneous dynamic weight of a single axle is double the dynamic wheel weight at the same instant of time, assuming that the wheels at the two ends of the axle have equal static weights. However, if the sprung mass is rolling or the unsprung mass is subjected to tramp movement, or both, the instantaneous weights of wheels on the two sides of the axle are different. By the same token, the pitch movement of the sprung and unsprung masses changes the instantaneous weights between the axles. Moreover, the summation of the weights of all wheels at the same instant of time does not necessarily equal the gross weight of the truck, because of various movements of sprung and unsprung masses.

## SUMMARY AND CONCLUSIONS

The load applied by trucks on the pavement structure varies from one instant of time to another. This variation in the dynamic load is largely affected by road roughness, truck speed, and suspension type and to some extent by tire pressure. For example, previous studies indicate that the instantaneous truck wheel load can vary from 25 to 175 percent of the static wheel load for walking beam suspension at 50 mph on medium-roughness roads.

WIM devices provide weights different than the static weight because of the instantaneous variations in the dynamic weight. Current WIM devices are one-sensor devices that provide a snapshot of the dynamic load spectrum. Thus, they do not fully represent the dynamic activity of the vehicle wheel load. Multisensor WIM devices are more capable of representing the actual wheel load distribution. The larger the number of sensors in a WIM device, the larger the accuracy in representing the dynamic load spectrum. Multisensor WIM devices can be used to estimate both the mean and the standard deviation of the dynamic wheel forces applied by the tires on the pavement. A larger number of sensors is required to accurately estimate the standard deviation than the number required to accurately estimate the mean. Also, the chance of underestimating the actual standard deviation is larger than that of overestimating the actual standard deviation.

Pavement performance is affected by dynamic loads more than by static loads. It is therefore recommended that the legal load limit, taxation, and penalties, as well as pavement design and analysis, could be better controlled in terms of the dynamic wheel forces actually applied on the pavement rather than the static weight. The dynamic wheel forces can be represented by the average and the standard deviation of the dynamic forces. Also, FHWA could have more influence on truck manufacturing with regard to suspension type and other vehicle characteristics to ensure slow pavement deterioration. These suggestions, however, need further refinement and research to provide the proper implementation procedure and to separate the dynamic forces caused by truck factors and road factors.

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