

# A Study Of Dynamic Wheel Loads Conducted Using A Four-Post Road Simulator

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## ABSTRACT

This paper describes the equipment, methodology, and results of a study of dynamic wheel loads generated by a two-axle truck. The main piece of testing equipment was a four-post road simulator. Two types of suspension, steel leaf spring and air, were mounted interchangeably on the same truck. Other test variables included tire type, tire inflation pressure, axle static load, vehicle speed, and road roughness. The wheel loads were characterized by a Dynamic Load Coefficient (DLC), defined as the ratio of standard deviation over mean wheel load. The results of the measurements were used to develop regression models of DLC as a function of test variables. The effect of the test variables on pavement wear was evaluated.

## INTRODUCTION

The progressive deterioration of civil infrastructure, including roads, bridges, tracks, and airport runways, is inevitable. However, the extent of deterioration and the rate at which it progresses vary substantially depending on vehicle and infrastructure characteristics and environmental conditions. One of the factors contributing to infrastructure wear is dynamic loading applied by heavy vehicles. The main objective of the study described in this paper was to investigate the effects of vehicle and road characteristics on the magnitude of dynamic pavement loading.

The methodology employed in this study and the testing program have been described in detail by Kenis et al. [1]. Some preliminary results of analysis of the data collected in the testing program have been discussed by Kulakowski et al. [2]. This paper focuses on the effects of tire type (dual and single wide-base tires), suspension type (steel and air), tire inflation pressure, wheel static load, vehicle speed, and road roughness on dynamic tire forces. The pavement damaging potential of

the truck with different tire types and different suspensions was assessed under conditions of randomly distributed and spatially repeatable tire forces. Most of the data used in the analysis were collected in experiments conducted on the road simulator. Some of these data were compared with the data obtained in field tests conducted on in-service roads.

## TEST EQUIPMENT

The two main pieces of equipment used in this study were the test vehicle and the road simulator.

The test vehicle was a Navistar International S series flat-bed two-axle truck, model 1957, assembled in 1980, shown graphically in figure 1. The front-axle suspension of the truck is a constant-rate leaf spring assembly. A progressive-rate leaf spring assembly is used on the rear axle. The rear-axle steel suspension was changed during the testing program to air suspension with tapered leaf spring. The test vehicle was instrumented with strain gages, accelerometers, and LVDT's to measure dynamic tire forces and accelerations and displacements of the sprung and unsprung masses. The sensor power supply, signal conditioning, and data acquisition equipment were installed in the cab of the truck.

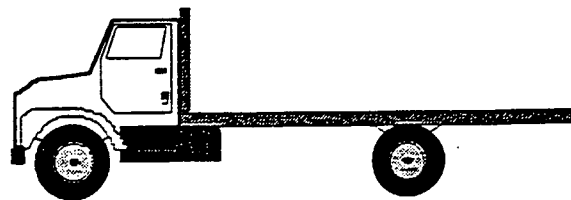


Figure 1. Two-axle flat-bed truck used in the study.

The road simulator, called DYNTRAC, was a four-post servohydraulic actuation system. During testing the test vehicle rests on wheel pans attached to the pistons of the hydraulic actuators. The displacements of the 156-kN actuators are controlled by a computer to follow a desired road profile. The maximum stroke of the actuators is 15.2 cm. The actuators' performance is tuned by a controller using piston position and differential pressure feedback. In general, actuators are unable to follow the input profile exactly due to inherent inertia of the mechanical and hydraulic system components. To obtain the same vehicle response on a road simulator as in road tests, the actuator excitation signals are adjusted iteratively until a selected variable of the vehicle dynamics, such as suspension deflection or acceleration of sprung mass, matches the measurements of the same variable obtained in field tests. This process, called Remote Parameter Control (RPC), has been used with mixed results in studies of dynamic wheel loads [3]. In order to evaluate the performance of the actuators, they were subjected to an input white noise signal with frequency cutoff of 50 Hz. Figure 2 shows the power spectral densities of the input signal and the actuator displacement. It can be seen that there is a good match between the two spectra over the frequency range up to approximately 20 Hz, which should allow the profile harmonics responsible for generating tire forces to be reproduced by the actuators without significant deformations. Figure 3 shows a profile of a medium-roughness road with an IRI value of 2.6 mm/m and the actuator displacement in a test involving a truck traveling at 48 km/h. For higher speeds and higher road roughness the agreement between the input profile and the actuator displacement is not as good but it is believed that the truck is still subjected to the same critical frequency components as those present in the input profile. In general, however, the roughness index of the actuator displacement signals was lower than the roughness of actual road sites and, consequently, the magnitude of dynamic tire forces on DYNTRAC was somewhat lower than on corresponding road sites, as illustrated by figure 4.

In spite of the differences in magnitudes of dynamic loading generated on the road simulator and in road tests, the relationships between DLC and test variables, including road roughness, vehicle speed, and static load developed from the two data sets were very similar. A linear regression model of DLC as a function of the test variables derived from the road simulator data was

$$\text{DLC} = 0.0391 + 0.022 r + 0.0006 v - 0.0014 L \quad (1)$$

where

$r$  - international roughness index, mm/m,

$v$  - vehicle speed, km/h,

$L$  - static wheel load, kN.

The same model derived from the road data was

$$\text{DLC} = 0.0449 + 0.019 r + 0.0007 v - 0.0011 L \quad (2)$$

The two models are very similar. The results presented in the remainder of the paper were derived using the data collected in experiments conducted on the road simulator.

## EFFECTS OF TEST VARIABLES ON DLC

The test variables included tire type, suspension type, road roughness, vehicle speed, axle load, and tire inflation pressure.

### EFFECT OF TIRE TYPE

Three tire types were tested: standard radial dual tire, low-profile dual tire, and wide-base single tire. A full factorial experiment was conducted with each tire type and all combinations of the following variables: road roughness at three levels (low, medium, and high), vehicle speed at four levels (24, 48, 72, and 89 km/h), axle static load at four levels (corresponding to truck empty, and payloads of 17.6, 35.2, and 61.6 kN), and tire inflation pressure at three levels (483, 587, and 690 kPa for dual tires and 621, 725, and 828 kPa for wide-base tires). The values of DLC for the same combinations of test variables and different tires were then compared and the following regression models were derived:

$$\text{DLC}_{\text{SR}} = 1.02 \text{ DLC}_{\text{LP}} \quad (3)$$

$$\text{DLC}_{\text{WB}} = 0.90 \text{ DLC}_{\text{LP}} \quad (4)$$

$$\text{DLC}_{\text{WB}} = 0.88 \text{ DLC}_{\text{SR}} \quad (5)$$

where subscripts SR, LP, and WB refer to standard radial, low-profile, and wide-base tires, respectively. The distribution of the experimental data is shown in figures 5, 6, and 7. These results indicate that the two dual tires generate essentially the same dynamic loads, whereas the wide-base single tire generates 10 to 12 percent lower DLC's than either dual tire. The reason for the lower dynamic loads generated by the truck with wide-base tires is the much smaller spring constant of these tires, compared with the spring constants of the dual tires [2]. It will be shown later, however, that in spite of the smaller magnitude of dynamic loads, the pavement damaging potential of the wide-base single tires is greater than that of the dual tires.

### EFFECT OF SUSPENSION TYPE

To investigate the effect of suspension type on dynamic pavement loading, the truck's rear-axle progressive leaf spring suspension was replaced by an air

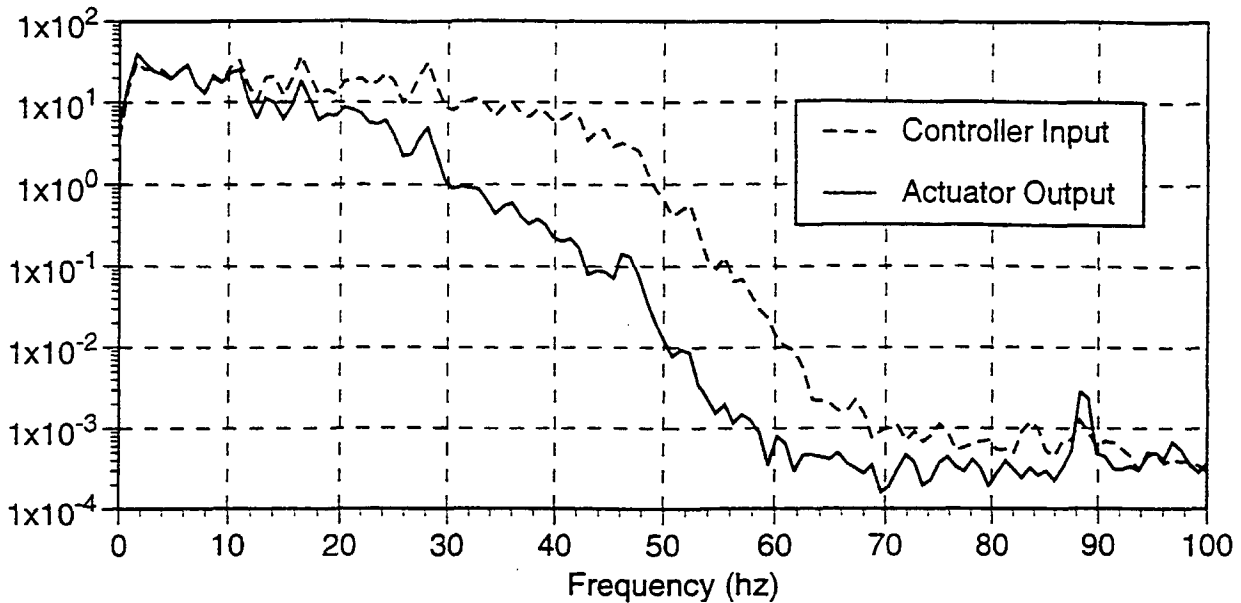


Figure 2. Power spectral densities of input profile and actuator displacement.

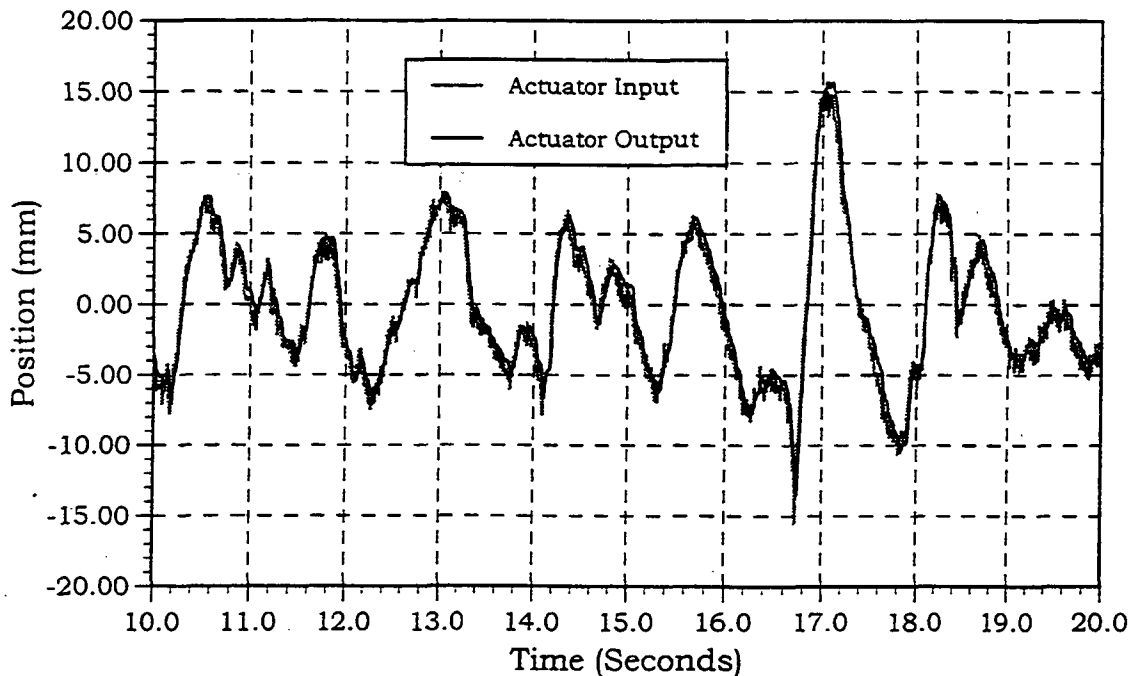


Figure 3. Actuator input and output for a medium roughness profile and speed of 48 km/h.

suspension. The truck with air suspension was then subjected to the same series of tests as those conducted with the steel suspension.

First, to obtain an overall comparison of performance of the two suspensions, a simple regression model was derived relating values of DLC obtained with the two suspensions and standard radial tire on both axles, and for all combinations of the remaining test variables. The following equation was obtained:

$$DLC_S = 1.04 DLC_A \quad (6)$$

where subscripts S and A refer to steel and air suspensions, respectively. Figure 8 shows the distribution of the experimental data and the regression line given by equation 6. Upon careful inspection of the data shown in figure 8, it can be observed that in the lower range of DLC's, roughly less than 0.15, most data points lie above the regression line, whereas in the higher range of DLC's, roughly greater than 0.15, the data points are located mostly below the regression line. To verify this observation, the experimental data used in the derivation of equation 6 were divided into two sets. The first set included all data points with values of steel suspension

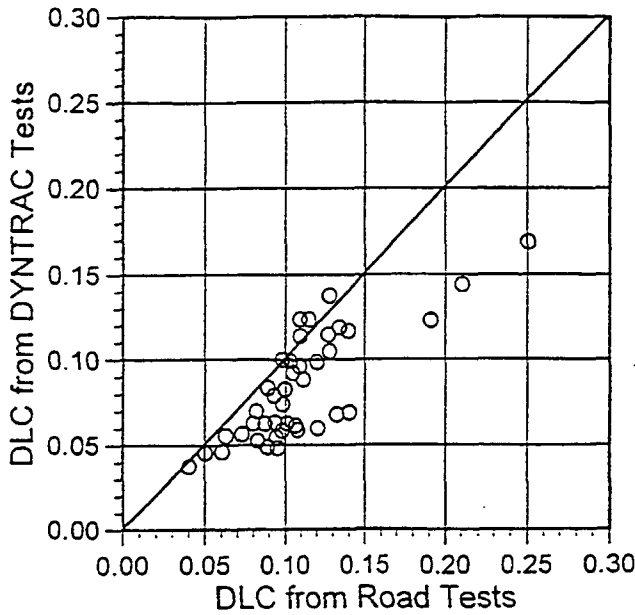


Figure 4. DLC's from road simulator versus DLC's from road tests.

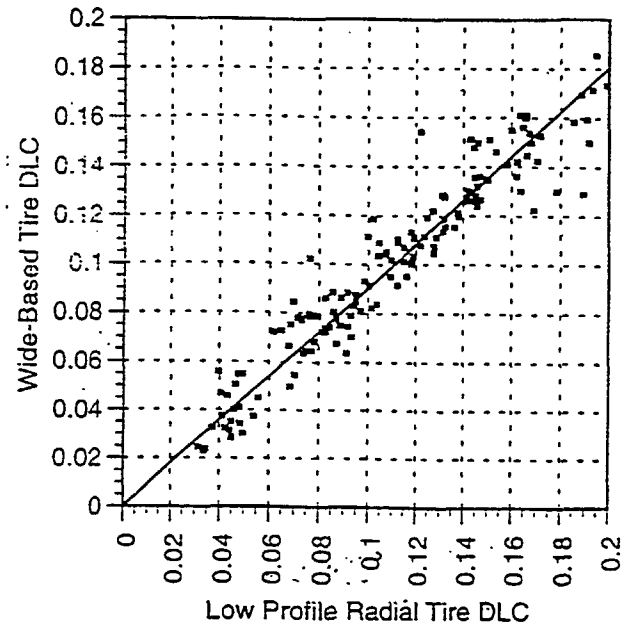


Figure 6. DLC's of wide-base tire versus low-profile tire.

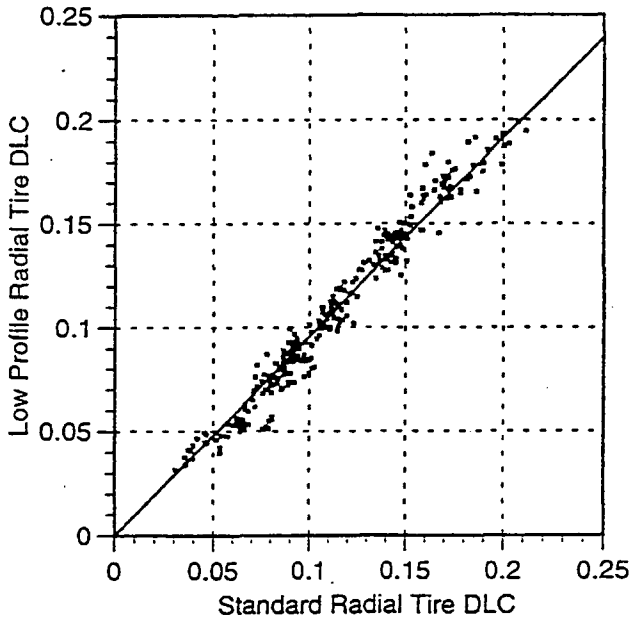


Figure 5. DLC's of standard radial tire versus low-profile tire.

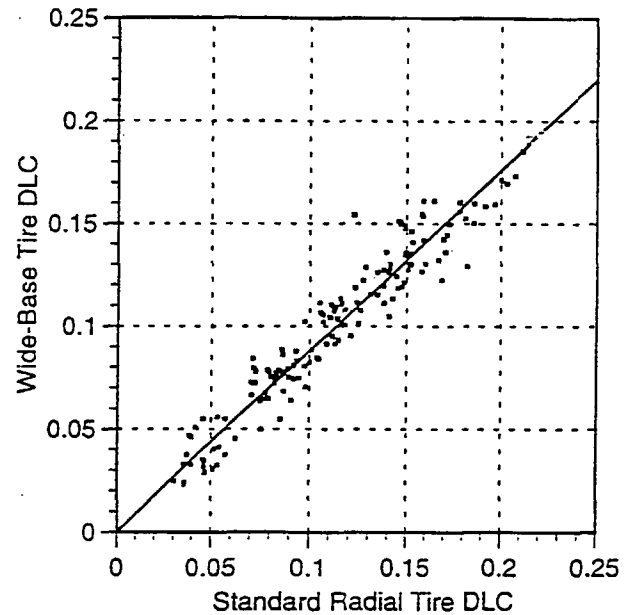


Figure 7. DLC's of wide-base tire versus standard radial tire.

DLC being smaller or equal to 0.15, and the second set with steel suspension DLC's greater than 0.15. A linear regression was then performed on the two data sets and the following models were obtained:

$$\frac{DLC_s}{DLC_A} = 1.18 \quad \text{for } DLC_s \leq 0.15 \quad (7)$$

$$\frac{DLC_s}{DLC_A} = 0.93 \quad \text{for } DLC_s \geq 0.15 \quad (8)$$

It can thus be concluded that a simple statement that air suspension generates lower dynamic loads than steel suspension would be very misleading. For the particular type of vehicle tested in this study, air suspension proved indeed to be superior to steel suspension, but only for those combinations of road roughness, speed, and axle load for which the values of DLC with steel suspension are smaller than approximately 0.15. In general, air suspensions are considered to generate lower dynamic loads than steel suspensions [4]. However, some

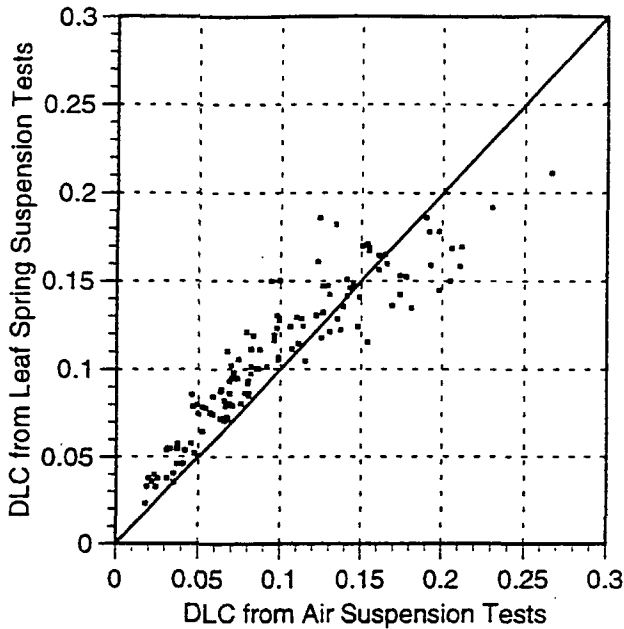


Figure 8. Correlation between steel and air suspension DLC's.

researchers have reported tests in which air suspension did not offer any benefits over steel suspension in terms of dynamic pavement loading [3]. The results obtained in this study clearly demonstrate that the benefits of using air suspension instead of steel suspension must be evaluated with great care and that there is no basis for expecting either suspension type to be superior for all vehicle designs and operating conditions.

#### EFFECTS OF ROAD ROUGHNESS, SPEED, LOAD, AND TIRE INFLATION PRESSURE

To evaluate the effects of road roughness, vehicle speed, static load, and tire inflation pressure on dynamic pavement loading, linear regression models of DLC as a function of the test variables for three tire types with the truck equipped with steel suspension were derived. The following equations were derived for the rear-axle wheel:

$$DLC_{SR} = -0.0299 + 0.034 r + 0.0012 v - 0.0009 L + 0.042 \cdot 10^{-3} P_t \quad (9)$$

$$DLC_{LP} = -0.0269 + 0.034 r + 0.0012 v - 0.0007 L + 0.018 \cdot 10^{-3} P_t \quad (10)$$

$$DLC_{WB} = -0.0258 + 0.028 r + 0.0011 v - 0.0006 L + 0.025 \cdot 10^{-3} P_t \quad (11)$$

where

$P_t$  - tire inflation pressure, kPa.

The above equations are very similar, especially when one looks at the road roughness and vehicle speed terms. The effects of the different test variables on dynamic loading can be further evaluated quantitatively using DLC sensitivity parameters [2]. The DLC sensitivity,  $S_i$ , with respect to variable  $x_i$  is defined as

$$S_i = \frac{\partial DLC}{\partial x_i} \bar{x}_i \quad (12)$$

where  $\bar{x}_i$  is a baseline value of variable  $x_i$ . Another useful measure of the effects of the test variables on DLC's is the relative percentage change of the variable necessary to produce a change in DLC of 0.01, defined by

$$\delta_i = \frac{\Delta x_i}{\bar{x}_i} 100\% \quad (13)$$

where the absolute change of the test variable  $x_i$  is given by

$$\Delta x_i = 0.01 \frac{\bar{x}_i}{S_i} \quad (14)$$

It can be shown that the two sensitivity parameters are simply related:

$$\delta_i = \frac{1}{S_i} \quad (15)$$

The values of  $\delta_i$  (where subscript  $i$  indicates the test variable), listed in table 1, indicate that a change in DLC of 0.01 can be caused by a change in vehicle speed of 11 to 13 percent (8 to 10 km/h), a change in road roughness of approximately 15 percent (0.3 mm/m), a change in axle static load of 40 to 60 percent (10 to 17 kN), or a change in tire inflation pressure of 40 to 100 percent (230 to 580 kPa) for dual tires and of approximately 55 percent (400 kPa) for wide-base single tires. It can thus be concluded that vehicle speed and road roughness have a very strong effect on dynamic loading, axle static load has a moderate effect, and tire inflation pressure has a very small effect on DLC.

Table 1. Percent changes of test variables necessary to change DLC by 0.01.

Tire Type	$\delta_v$	$\delta_r$	$\delta_L$	$\delta_{P_t}$
Standard Radial	11.8	14.1	-38.1	40.6
Low-Profile	11.3	13.9	-50.4	92.6
Wide-Base	12.6	16.6	-60.5	55.7

## EFFECT OF TIRE AND SUSPENSION TYPES ON PAVEMENT DAMAGE

To assess a truck's pavement damaging potential, Eisenmann et al. [5] proposed a road stress factor defined as

$$\Phi = (\eta_1 \eta_2 L)^4 (1 + 6s^2 + 3s^4) \quad (16)$$

where

$\eta_1$  - coefficient reflecting wheel configuration (1.0 for wheels with single tires and 0.9 for wheels with dual tires),

$\eta_2$  - coefficient reflecting tire-pavement contact pressure,

$s$  - coefficient of variation of dynamic wheel load.

The coefficient  $\eta_2$  is assumed to be a linear function of the tire-pavement contact pressure,  $P_c$ ,

$$\eta_2 = 0.65 + 0.5 P_c \quad (17)$$

where  $P_c$  is in  $N/mm^2$ . The coefficient of variation of dynamic wheel load is usually replaced by DLC. A dynamic road stress factor is defined as

$$\nu = 1 + 6s^2 + 3s^4 \quad (18)$$

It is still not known for sure whether Eisenmann's road stress factor provides an appropriate and accurate measure of a vehicle's pavement damaging potential. Equation 16 was derived assuming that dynamic loads are randomly distributed along the road. In fact, since peak wheel loads are generated by heavy vehicles in response to road profiles and since the dynamic characteristics of heavy vehicles travelling on a particular road tend to be similar, the dynamic wheel loads are expected to be spatially repeatable (i.e., peak loads are applied at specific locations along the road) [6]. Nevertheless, the Eisenmann's road stress factor was considered to be appropriate for comparison of the pavement damaging potential of the same vehicle with different types of tires and different suspensions.

The following baseline values of the test variables were used:

$P_c = 587$  kPa for dual tires and 724 kPa for wide-base tires,

$v = 89$  km/h,

$r = 2.05$  mm/m,

$$L = 29.7 \text{ kN (14.85 kN per dual tire).}$$

The results of the calculations are presented in table 2. It can be seen that the pavement damaging potential of the test truck used in this study is about the same for the two dual tires but increases by approximately 80 percent when single wide-base tires are used.

Table 2. Results of calculation of road stress factor for three tire types.

Tire Type	Standard	Low-Profile	Wide-Base
DLC	0.1413	0.1414	0.1310
$\nu$	1.1212	1.1212	1.1041
$\eta_1$	0.9	0.9	1.0
$P_c, N/mm^2$	0.56	0.62	0.73
$\eta_2$	0.93	0.96	0.98
$\phi, 10^{-16}, kN^4$	42.82	43.36	79.24

In order to compare the pavement damaging potential of the truck with steel and air suspensions one may notice that

$$\frac{\Phi_S}{\Phi_A} = \frac{\nu_S}{\nu_A} \quad (19)$$

Using the same baseline values of the test variables as before, the following values of the dynamic road stress factor for the air suspension are obtained:

$$\nu_A = 1.0712 \quad \text{for standard radial tires}$$

and

$$\nu_A = 1.0452 \quad \text{for wide-base tires.}$$

These values are 5 to 6 percent lower than the values of the dynamic road stress factor for the truck with steel suspension listed in table 2.

As pointed out earlier, Eisenmann's road stress factor formula assumes randomness of dynamic wheel loads and, therefore, underestimates the pavement damaging potential. Sweatman [7] suggested that the severity of the dynamic loads can be better evaluated by the 95th percentile impact factor, which is estimated by

$$IF_{95th} = 1 + 1.645 \text{ DLC} \quad (20)$$

and by the corresponding road stress factor

$$\Phi_{95th} = (IF_{95th})^4 \quad (21)$$

The results of the comparison of steel and air suspensions with standard radial and wide-base tires are shown in table 3. It can be seen that the values of the 95th percentile road stress factor for air suspension are approximately 20 and 30 percent lower than the values obtained for the steel suspension with standard radial and wide-base tires, respectively.

The above results demonstrate that the pavement damaging potential of the truck with air suspension is smaller than when a steel suspension is used; however, the extent of the reduction of pavement damage depends in large part on the methodology used in the analysis.

Table 3. Values of 95th percentile road stress factor for steel and air suspensions.

	Steel Standard Radial	Air Standard Radial	Steel Wide Base	Air Wide- Base
DLC	0.1413	0.1084	0.1310	0.0848
$IF_{95th}$	1.2324	1.1783	1.2155	1.1395
$\Phi_{95th}$	2.31	1.93	2.18	1.69

## CONCLUSIONS

The results of the study demonstrate that the dynamic loads applied by heavy vehicles to pavements increase significantly when vehicle speed and road roughness increase. The type of dual tires and the tire inflation pressure were shown to have a negligible impact on dynamic loads. The pavement damaging potential of single wide-base tires is estimated to be approximately 85 percent higher than for dual tires. Air suspension produced lower dynamic loads in most cases, especially under the road and vehicle operating conditions that generated DLC's below 0.15. There were no benefits associated with air suspension, however, under the conditions where DLC was greater than approximately 0.15. Finally, the results indicate that the pavement damaging potential of the truck with air suspension is smaller than with steel suspension, but it is difficult to estimate by how much.

## ACKNOWLEDGEMENT

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