Sensitivity of Rear Wheel Pavement Loading to Variations in Heavy Vehicle Parameters, Speed, and Road Roughness

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To construct a heavy vehicle simulation model, it is necessary to obtain vehicle parameters. A sensitivity analysis has been completed that studies the effects of ±15 percent variations in vehicle parameters on rear wheel dynamic load coefficients and maximum vertical rear wheel/pavement forces. Four speeds and road profiles of low, medium, and high roughness were considered. Variations in wheelbase, vehicle curb weight, and payload weight were observed to cause significant variations in values of rear wheel dynamic load coefficients and rear wheel peak forces. In addition, inaccuracies in determination of rear suspension spring rate, rear suspension unsprung weight, and rear tire spring rate were shown to have a significant effect on rear wheel dynamic load coefficients, but not on rear wheel peak forces.

The process of deterioration of the nation's highway structures has accelerated considerably in recent years because of a significantly higher percentage of truck traffic on the highway system. Moreover, trucks have become longer and wider and they carry heavier loads. Many research studies are currently under way to determine the effects of heavy vehicle parameters on dynamic tire forces and on the pavement damage for which these forces are responsible. Computer simulation of heavy vehicle dynamics offers a useful tool for investigation of dynamic pavement loading. The accuracy and the validity of computer simulation results depend very strongly on the accuracy of the vehicle parameters used in the simulation. In this study of vehicle-pavement loading, a two-axle, 155 750-N (35,000-lb) truck with an empty weight of 66 750 N (15,000 lb) and a payload of 89 000 N (20,000 lb) was modeled using the Phase-4 simulation program. During the course of measuring the truck parameters, it was important to know the measurement accuracy necessary to ensure reasonable accuracy of computer simulation results. A sensitivity analysis was performed to determine the effects of truck parameter variations on the simulated truck tire forces. The results of the sensitivity analysis allow identification of the most critical parameters, which have to be measured with high accuracy, as well as the parameters that can be roughly estimated without significantly degrading the quality of the overall vehicle dynamics model. Actual truck parameters were measured (*1*), and the results of the measurements were used as the baseline in the sensitivity analysis. Simulation results using the measured parameters were also compared with dynamic experimental results (*1*).

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BACKGROUND

Various researchers have studied the effects of vehicle geometry, inertial parameters, and speeds on pavement loading (*2–8*). Such efforts considered how pavement loading increased or decreased as parameters were varied. Lin et al. (*9*) focused on changes in front tire pavement load sensitivity to variations in parameter values at various vehicle speeds and pavement roughness values. The present effort focuses on change in rear tire pavement load sensitivity to variations in parameter values at different vehicle speeds and pavement roughness values.

Lin et al. (*9*) discuss various truck simulation models including the ASTM Dynamics model (*10*), VESYM and MAKEVIN, a personal computer (PC)-based pitch plane model (*11*), and the Phase 4 simulation program (*12*). They state

> The Phase 4 simulation program includes a reasonable level of complexity for vehicle simulation and parameter studies and was the program of choice for the present studies. Issues involved in this decision included the availability and familiarity of this code, as well as its history of use over the past few years.

Phase 4 was also the simulation program of choice for the present study. A linear spring-damper model was used for the tires, and a nonlinear model including coulomb friction was employed to represent the truck suspension. Comparison of the Phase 4 program with other simulation programs and with experimental data was previously reported (*13–15*).

Definitions of quantitative pavement load measures are first presented. Actual road profiles were used as inputs for a vehicle parameter sensitivity analysis. Parameter simulation results are studied to gain insight into the effects of various vehicle parameters on rear wheel/pavement loads. Results offer qualitative as well as quantitative insight into parameter variation effects on rear wheel dynamic pavement loading.

QUANTITATIVE MEASURES OF PAVEMENT LOADS

To systematically interpret and analyze vehicle dynamics simulation data, quantitative measures of mean force ($\overline{F}$), maximum force (F_{max}), and dynamic load coefficient (DLC) are first defined. These measures are calculated in terms of Phase 4 outputs of tire force F (left front, right front, left rear, and right rear) versus time

t. For N, data points representing tire force (time function), mean force ($\bar{F}$), maximum force (F_{max}), and dynamic load coefficient (DLC) are defined for each tire as follows:

$$\bar{F} = \frac{\sum_{i=1}^{N} F_i}{N} \quad (1)$$

$$F_{max} = \text{Max } \{F_i, i = 1, N\} \quad (2)$$

$$DLC = \frac{s}{\bar{F}} \quad (3)$$

where s is the standard deviation of tire force F. All tire forces in this study are positive.

Mean force represents the time average of tire force in the entire simulation period. It should be similar in magnitude to the static tire force. Maximum force represents the largest tire factor in the entire simulation time history. The dynamic load coefficient is a statistical measure reflecting tire force deviation from a mean value. It is helpful to note that the DLC is more a measure of oscillation about a mean value than a reflection of peak pavement loading (*9*).

SENSITIVITY ANALYSES

DLC and F_{max} were calculated for each wheel. These two quantities are considered the desired measures in the sensitivity analysis. Sensitivity (λ) is defined in the same manner as in a previous study (*9*). Sensitivity (λ) is defined as the percentage change in the desired output when an input parameter changes by 30 percent (115 to 85 percent). Sensitivity λ is calculated as follows:

$$\lambda(Y, x_i) = \frac{[Y(x_1, x_2, \ldots, x_i + \delta x_i, \ldots, x_n) - Y(x_1, x_2, \ldots, x_i - \delta x_i, \ldots, x_n)]}{[Y(x_1, x_2, \ldots, x_i, \ldots, x_n)]} * 100 \text{ percent} \quad (4)$$

TABLE 1 Nominal Vehicle Parameters Used in Phase 4 Simulations

	VALUE	UNIT
1.TRUCK PARAMETERS		
Wheelbase	218.25	in
Base vehicle curb weight on front suspension	5890	lb
Base vehicle curb weight on rear suspension	3776	lb
Sprung mass CG height	39	in
>Roll moment of inertia	8630	in-lb-sec^2
>Pitch monent of interia	127000	in-lb-sec^2
>Yaw moment of inertia	135600	in-lb-sec^2
Payload weight	10000	lb
>Distance ahead of rear suspension center	20	in
>CG height (in. above ground)	85	in
>Roll moment of inertia	16000	in-lb-sec^2
>Pitch moment of inertia	39000	in-lb-sec^2
>Yaw moment of inertia	39000	in-lb-sec^2
2. FRONT SUSPENSION AND AXLE PARAMETERS		
Suspension spring rate	850	lb/in/side
Suspension viscous damping	50	lb-sec/in/side
Coulomb Friction	300	lb/side
Axle roll moment of inertia	3630	in-lb-sec^2
Roll center height (in. above ground)	18.6	in
Auxiliary roll stiffness	7410	in-lb/deg
Lateral distance between suspension spring	35	in
Track width	80.5	in
Usprung weight	1260	lb
3. FRONT TIRES AND WHEELS		
Cornering stiffness (app. 10% of static load)	355	lb/deg/tire
Longitudinal stiffness (app. 4 times tire static load)	14200	lb/slip/tire
Aligning moment	1200	in-lb/deg/tire
Tire spring rate	5173	lb/in/tire
Tire loaded radius	19	in
Polar moment of inertia	103	in-lb-sec^2/wheel
4. REAR SUSPENSION AND AXLE PARAMETERS		
Suspension spring rate	3790	lb/in/side
Suspension viscous damping	20	lb-sec/in/side
Coulomb friction	1312.5	lb/side
Axle roll moment of inertia	4474	in-lb-sec
Roll center height (in. above ground)	31	in
Roll steer coefficient	0.0235	deg steer/deg roll
Auxiliary roll stiffness	12577.5	in-lb/deg
Lateral distance between suspension spring	40.5	in
Track width	72	in
Unsprung weight	2310	lb
5. REAR TIRES AND WHEELS		
Dual tire separation	13.5	in
Cornering stiffness	855	lb/deg/tire
Longitudinal stiffness	34200	lb/slip/tire
Aligning moment	1200	in-lb/deg/tire
Tire spring rate	5173	lb/in/tire
Tire loaded radius	19	in
Polar moment of inertia	103	in-lb-sec^2/wheel

where

Y = desired measure (DLC or F_{max}),
x_i = input parameter (nominal values of truck parameters as given in Table 1),
$\delta x_i = 0.15x_i$, and
$y = Y(X) = Y(x_1, x_2, \ldots, x_i, \ldots, x_n)$ = function of all Phase 4 input truck parameters.

No cross sensitivity is considered here, and parameters are changed one at a time. Although the test truck model is assumed symmetrical around its center, differences between left and right wheel forces arise because of differences in left and right input road profiles. Roll motion of both the body and axles is included in the Phase 4 simulations.

First, sensitivity of left front and rear tire forces to variations in each of the Phase 4 input parameters is considered at a highway cruise speed of 97 km/hr (60 mph) and for a medium roughness road. Second, the effect of vehicle speed and road roughness on tire force sensitivity is studied for a subset of Phase 4 parameters.

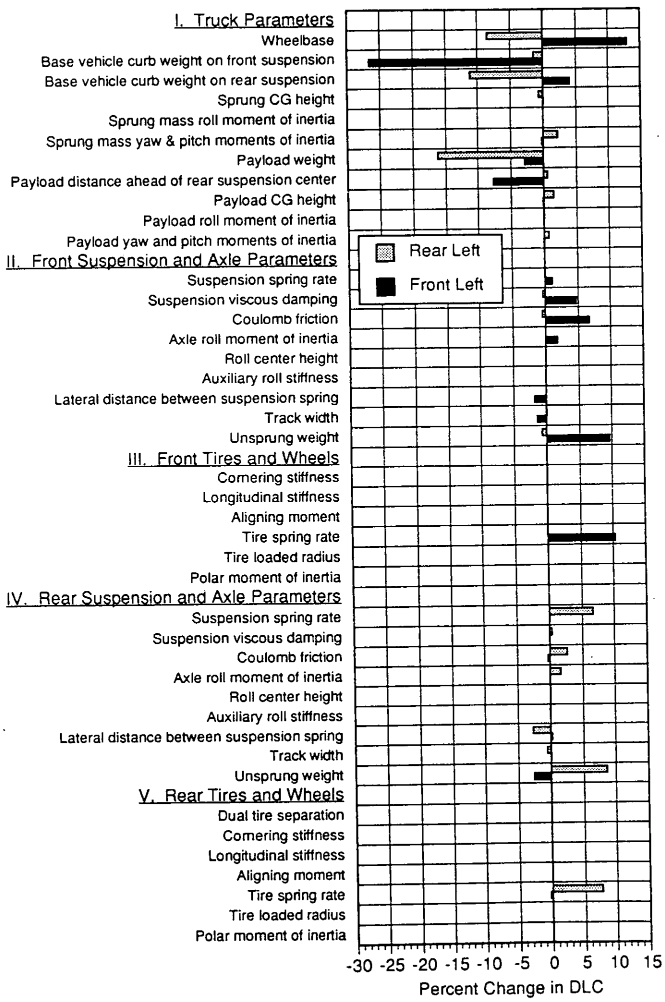

FIGURE 1 Effects of 30 percent increase in truck parameters on left front and rear tire DLC at 97 km/hr (60 mph) (*9*).

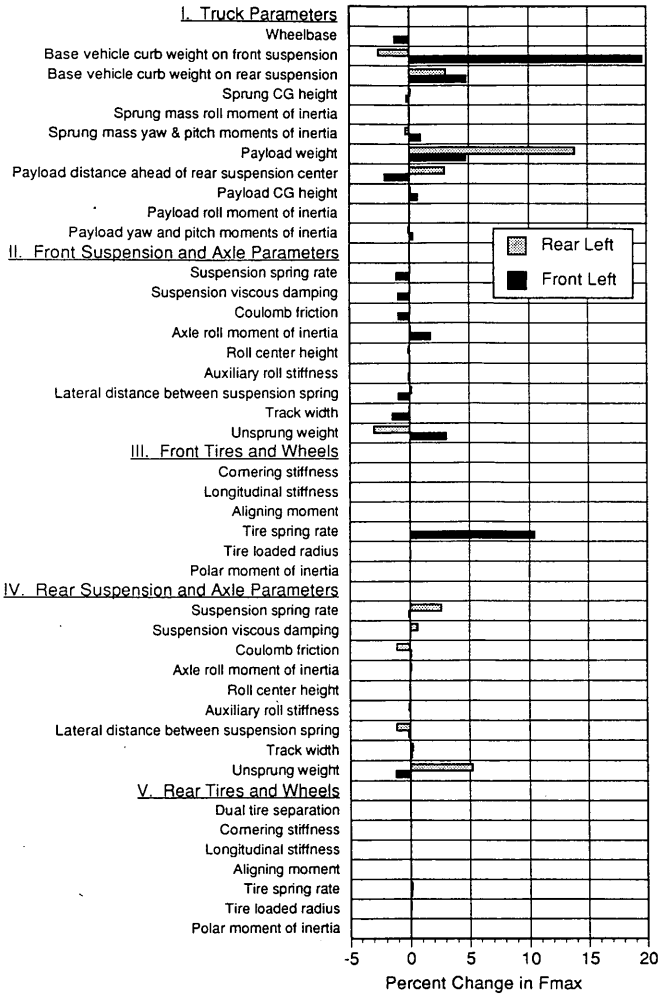

FIGURE 2 Effects of 30 percent increase in truck parameters on left front and rear maximum tire force at 97 km/hr (60 mph) (*9*).

Road Profiles

Three road profiles were used in this study: low, medium, and high roughness. Experimental road profile data were used, and left and right wheel track roughness numbers according to the international roughness index (IRI) were as follows: low roughness, right—1.24 m/km (78.3 in./mi); left—1.11 m/km (70.2 in./mi); medium roughness, right—2.64 m/km (167.4 in./mi), left—3.01 m/km (190.8 in./mi), high roughness, right—3.97 m/km (251.2 in./mi), left—3.86 m/km (244.8 in./mi). A 152.4-m (500-ft) pavement length was used in this study. All large irregularities (potholes) in road profiles were removed (*16*).

Results of Sensitivity Analysis

Sensitivity of DLC and of F_{max} to variations in system parameters is reported in Figures 1 and 2, respectively. A highway cruise speed of 97 km/hr (60 mph) and the medium roughness profile were used for the simulations of Figures 1 and 2. The sensitivity plots of Figures 1 through 10 are used as follows. To study the

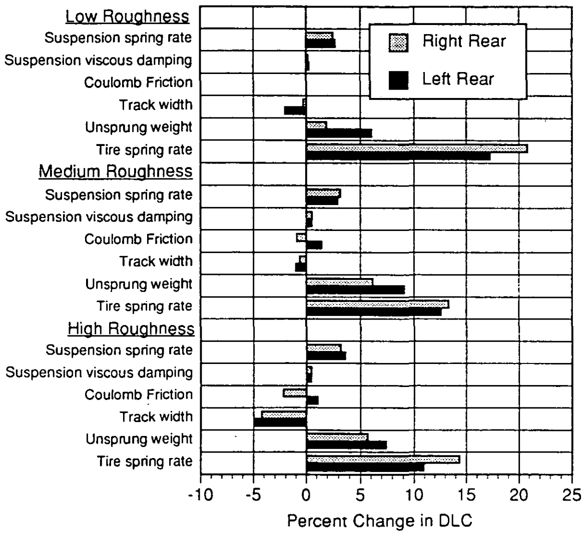

FIGURE 3 Effects of 30 percent increase in truck parameters on left rear tire *DLC* for three roughness levels at 48 km/hr (30 mph).

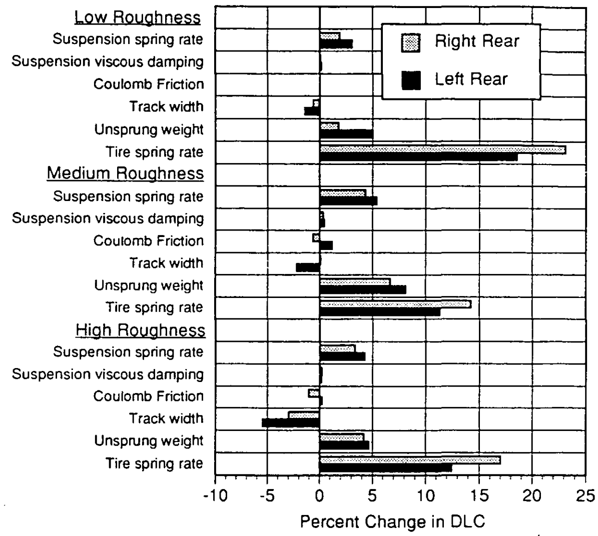

FIGURE 5 Effects of 30 percent increase in truck parameters on left rear tire *DLC* for three roughness levels at 72 km/hr (45 mph).

effect of a 30 percent increase in rear suspension spring rate (115 percent × rear suspension spring rate − 85 percent × rear suspension spring rate), the first line in Section IV of Figure 1 would be considered. A 30 percent increase in rear suspension spring rate is observed to result in a rear left tire *DLC* increase of about 7 percent and a front left tire *DLC* change of less than 1 percent. It can be seen that base vehicle curb weight, payload weight, and payload suspension location each have a significant influence on *DLC* and F_{max}. This is not surprising because each of these parameters has a direct and immediate impact on mean tire forces and on the heave mode resonance. In addition, it is not surprising that the wheelbase has a noticeable effect on *DLC* because the pitch mode oscillation is greatly affected by this parameter. Lin et al. (*9*) present a discussion of the effect of vehicle speed on the front wheel *DLC* and F_{max} sensitivities. In that study, parameters in Sections II and III of Figure 1 were varied and front wheel *DLC* and F_{max} were recalculated and reported for four speeds and three values of road roughness. Now a similar study has been completed for rear suspension and tire parameter variations listed in Sections IV and V of Figure 1. Specifically, the parameters in these sections, which are considered along with speed variations, are rear suspension spring rate, rear suspension viscous damping, rear suspension coulomb friction, rear wheel track width, rear suspension unsprung weight, and rear tire spring rate.

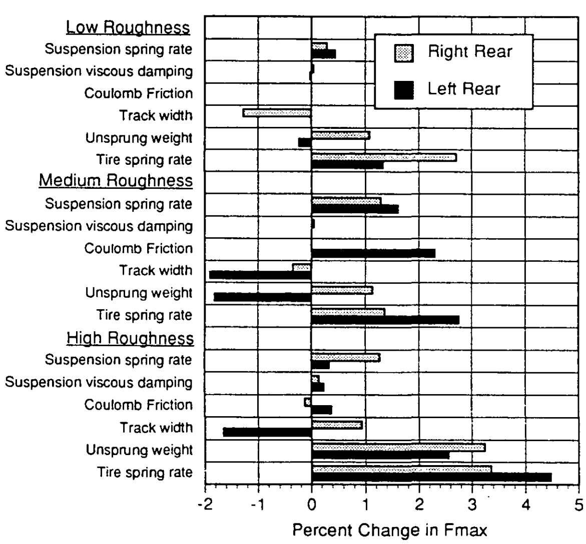

FIGURE 4 Effects of 30 percent increase in truck parameters on left rear maximum tire force for three roughness levels at 48 km/hr (30 mph).

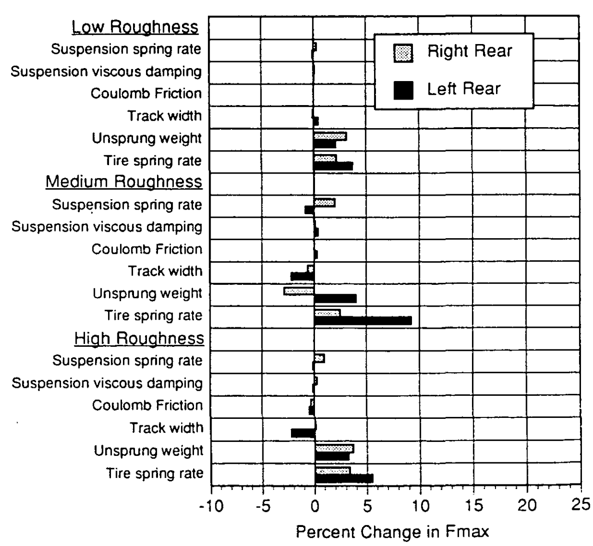

FIGURE 6 Effects of 30 percent increase in truck parameters on left rear maximum tire force for three roughness levels at 72 km/hr (45 mph).

DLC Sensitivity to Speed and Road Roughness

Figures 3 through 10 present *DLC* and F_{max} rear wheel sensitivity for speeds of 48, 72, 97, and 121 km/hr (30, 45, 60, and 75 mph), respectively. *DLC* and F_{max} are given for low, medium, and high roughness roads in each of these plots. The effects of both speed and road roughness, shown in Figures 3 through 10, have some very definite trends. At low speeds, 48 km/hr (30 mph), and for all three road roughness values, Figure 3 demonstrates that the predominant influence on *DLC* sensitivity is the tire spring rate. *DLC* is most sensitive to tire spring rate variation for low roughness roads. This is true for all four vehicle speeds, as shown in Figures 3 through 10. It is interesting to note that the effect of tire spring rate on *DLC* sensitivity tends to decrease with increasing speeds for all three road roughness values. An explanation of this phenomenon is given by recognizing that this sensitivity analysis says nothing about the magnitudes of *DLC* and F_{max} values. Rather, this study considers only the change in magnitude for variations in system parameters. Hence, the actual *DLC* value for a medium roughness road at high speeds might be larger than at low speeds, whereas the variation in spring rate on *DLC* sensitivity is observed to decrease with increasing speeds. It is likely that the magnitude of *DLC* increase as a result of a change in tire spring rate is relatively constant for increasing speeds. However, if the *DLC* magnitude increases with increasing speed, then the percentage increase in *DLC* will vary inversely with speed. The result is that inaccuracies in tire spring rate measurements will introduce less error into *DLC* calculations at high speeds and on high roughness roads than at low speeds and on low roughness roads. Usually there is more concern for dynamic pavement loading at high speeds and on rough roads than at low speeds and on relatively smooth roads because pavement damage increases with road roughness and speed (2). [Although pavement damage increases with vehicle speed, it may decrease at higher speeds as a result of decreasing dynamic response of the vehicle to pavement profile (2).]

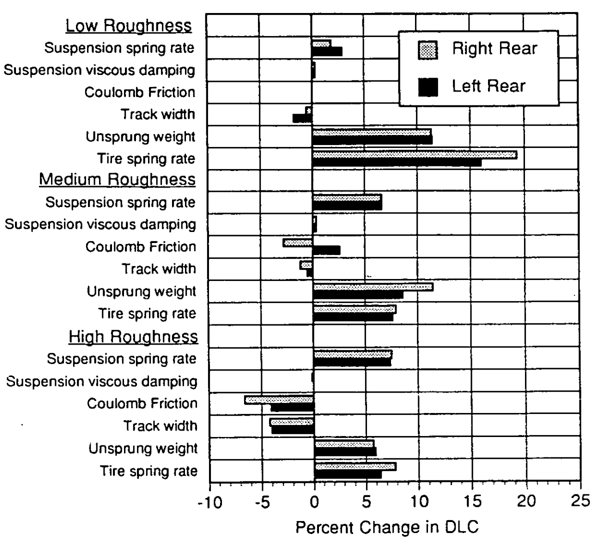

FIGURE 7 Effects of 30 percent increase in truck parameters on left rear tire *DLC* for three roughness levels at 97 km/hr (60 mph).

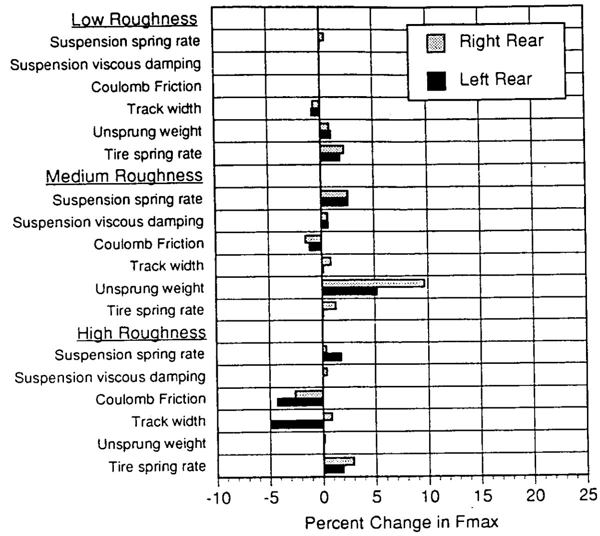

FIGURE 8 Effects of 30 percent increase in truck parameters on left rear maximum tire force for three roughness levels at 97 km/hr (60 mph).

In Figures 3, 5, 7, and 9, the effect of track width on *DLC* sensitivity at all speeds is seen to be greatest for the high roughness road. This observation might offer insight into the debate on the influence of vehicle roll on dynamic vertical wheel/pavement loads. Vehicle/tire roll oscillations are significantly affected by track width. For lower roughness roads the influence of track width and, hence, of vehicle or suspension roll, or both, is small. For high roughness roads the influence of track width and, hence, of vehicle or suspension roll, or both, is noticeable. A similar observation was made when front wheel *DLC* sensitivity was studied.

The results demonstrate that, for low roughness roads, vehicle speed has little effect on *DLC* sensitivity to suspension spring rate variation. However, when speed increases from 72 to 97 km/hr (45 to 60 mph) *DLC* sensitivity to a 30 percent variation in suspension spring rate more than doubles for both medium and high roughness roads.

DLC sensitivity to unsprung weight is relatively unaffected by speed for the high roughness road (see Figures 3, 5, 7, and 9). However, on the low roughness road, Figures 7 and 9 demonstrate that *DLC* sensitivity more than doubles when speed is increased from 72 to 97 km/hr (45 to 60 mph).

Coulomb friction variation primarily affects *DLC* sensitivity at the higher speeds of 97 and 121 km/hr (60 and 75 mph) and only for medium and high roughness roads.

Suspension viscous damping variation results in less than a 2 percent variation in rear tire *DLC* for all speeds and road roughness values considered. This might have been anticipated since there is relatively little viscous damping in the rear suspension of a two axle steel suspension vehicle. The effect of front suspension viscous damping on front tire *DLC* was observed to be more significant (9).

Table 2 is a *DLC* sensitivity matrix, summarizing the parameter effects that are shown in Figures 3 through 10. In this table, an "X" is entered in the appropriate row and column for each 5 percent change in *DLC*. Matrix locations are marked only when a 30 percent change in a system parameter resulted in a change in *DLC* of more than 5 percent. The average change between left and right wheel *DLC* was used in compiling this table, and numbers larger than 5 percent were rounded to the nearest 5 percent. A quick look at this table highlights the importance of accurate unsprung weight and tire spring rate measurements when simulations are used to calculate *DLC*. Suspension spring rate accuracy is most important at high speeds and high road roughness values. A 30 percent variation in coulomb friction measurement has greater than a 5 percent effect on *DLC* for only one speed and road roughness.

F_{max} *Sensitivity to Speed and Road Roughness*

Figure 4 demonstrates that, at 48 km/hr (30 mph), none of the parameters studied results in greater than a 5 percent change in F_{max}. In fact, the average rear left/right *DLC* variation is greater than 5 percent for only two parameter combinations: 30 percent tire spring rate variation at 72 km/hr (45 mph) on medium roughness road and 30 percent unsprung weight variation at 97 km/hr (60 mph) on medium roughness road. F_{max} is relatively insensitive to variations in suspension and tire system parameters. Variations in system parameters are observed to have a greater effect on rear *DLC* than on rear F_{max} for all three pavement roughness values and at all four vehicle speeds considered. This observation was also made in the study of front wheel *DLC* and F_{max} sensitivity (*9*). This conclusion, which should be very important for researchers studying pavement loading caused by dynamic forces applied by heavy vehicles, can be restated as follows: The maximum tire force that is capable of being generated on actual roads depends primarily on the vehicle curb weight and payload weight and is not significantly affected by variations and inaccuracies in suspension and tire parameters. The suspension and tire parameters are, however, critical for the manner in which the vehicle forces vary within the range of 0 to F_{max}. This also explains why *DLC* is sensitive to suspension and tire parameters since *DLC* depends

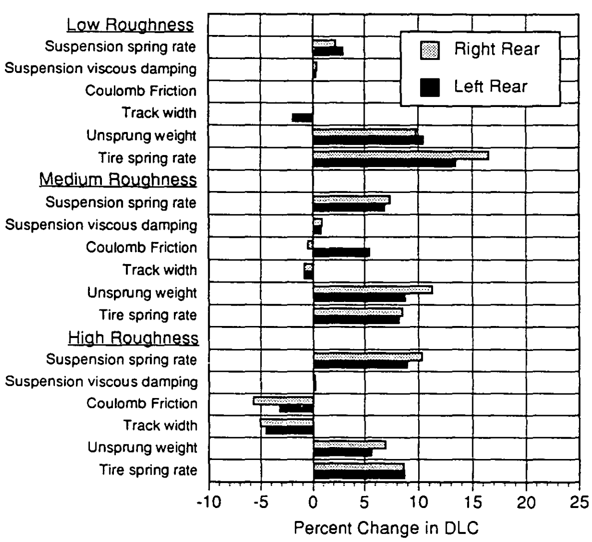

FIGURE 9 Effects of 30 percent increase in truck parameters on left rear tire *DLC* for three roughness levels at 121 km/hr (75 mph).

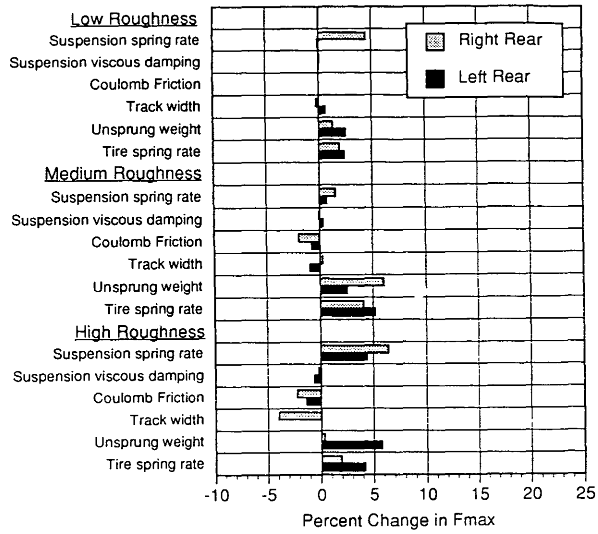

FIGURE 10 Effects of 30 percent increase in truck parameters on left rear maximum tire force for three roughness levels at 121 km/hr (75 mph).

on both the maximum tire force as well as on the variation of the tire force.

CONCLUSIONS

A two-axle, steel suspension truck model was assembled using the Phase 4 simulation program. Initial simulations using a medium roughness profile and a vehicle speed of 97 km/hr (60 mph) identified vehicle parameters having the largest effect on rear wheel *DLC* and F_{max}. Variations in rear suspension and rear tire parameters (suspension spring rate, suspension viscous damping, coulomb friction, track width, unsprung weight, and tire spring

TABLE 2 Rear Tire DLC Sensitivity Matrix

Figure # / Speed Km/hr / (Speed mph)	3 48 (30)	4 72 (45)	5 97 (60)	6 121 (75)
1. Low Roughness				
Suspension spring rate				
Suspension viscous damping				
Coulomb friction				
Track width				
Unsprung weight			XX	XX
Tire spring rate	XXXX	XXXX	XXX	XXX
2. Medium Roughness				
Suspension spring rate			X	X
Suspension viscous damping				
Coulomb friction				
Track width				
Unsprung weight	X	X	XX	XX
Tire spring rate	XX	XX	XX	XX
3. High Roughness				
Suspension spring rate			X	XX
Suspension viscous damping				
Coulomb friction			X	
Track width				
Unsprung weight		X	X	X
Tire spring rate	XXX	XX	X	XX

rate) were reported for four vehicle speeds and three road profiles of low to high roughness. For a 30 percent variation in each of these six parameters, rear suspension spring rate, rear suspension unsprung weight, and rear tire spring rate were observed to have the greatest effect on *DLC* over any range of speeds and road roughness values (see Table 2). Of the six rear suspension/tire parameters considered and for every speed and road profile used in these simulations, *DLC* was most sensitive to variations in tire spring rate.

The increased effect of track width on *DLC* for high roughness roads suggests that roll mode oscillations increase in importance with increased road roughness.

None of the six rear suspension/tire parameters was observed to significantly affect F_{max} over any range of speeds and road roughness values considered. The maximum rear tire force depends primarily on the vehicle curb weight and payload weight and is not significantly affected by variations or inaccuracies in suspension and tire parameters. The suspension and tire parameter measurements are, however, critical for the accurate determination of *DLC*

Future work might select vehicle parameters to be varied simultaneously, thereby studying parameter coupling effects on pavement loading. Also, alternative suspension systems, such as walking beam and air and more complex truck models such as tractor-trailer systems, might be studied.

ACKNOWLEDGMENTS

The work reported in this paper was partially sponsored by FHWA. Valuable input received from reviewers is gratefully acknowledged.

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The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the FHWA.

Publication of this paper sponsored by Committee on Surface Properties–Vehicle Interaction.