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"Roughness Index for Trucks"

A ROUGHNESS MODEL DESCRIBING HEAVY VEHICLE-PAVEMENT INTERACTION

by

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16. ABSTRACT
This study deals with the pavement roughness characteristics that affect pavement-heavy vehicle interaction. Dynamic vehicle response data from two sources was analyzed, namely experimental data obtained with the instrumented vehicle developed by the NRCC and simulated data obtained with a quarter-vehicle simulation. It was found that the vehicle response parameter of interest in this interaction is the sprung mass vehicle acceleration because it relates to both pavement/vehicle damage as well as to ride quality/cargo damage. The sprung mass vertical acceleration transfer function showed a distinct sensitivity to a pavement roughness excitation frequency of 3.5 Hz. A pavement roughness statistic was proposed based on the vertical sprung acceleration of the sprung mass. It is calculated by multiplying the spectral density of the roughness profile by the square of a reference transfer function and integrating the result. This procedure was implemented into a PC-based computer software program called TRRI (Truck Response to Roughness Index).

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EXECUTIVE SUMMARY

This study deals with the pavement roughness characteristics that affect pavement-heavy vehicle interaction. It presents a roughness model describing the pavement roughness attributes affecting heavy vehicle-pavement interaction. Dynamic vehicle response data from two sources was analyzed, namely experimental data obtained with the instrumented vehicle developed by the NRCC and simulated data obtained with a quarter-vehicle simulation.

It was found that the vehicle response parameter of interest in this interaction is the sprung mass vehicle acceleration because it relates to both pavement/vehicle damage as well as to ride quality/cargo damage. This was demonstrated by analyzing the transfer functions of both the dynamic axle load and the vertical sprung mass acceleration over a range of pavement roughnesses and vehicle speeds. The sprung mass vertical acceleration transfer function showed a distinct sensitivity to a pavement roughness excitation frequency of 3.5 Hz.

A pavement roughness statistic was proposed based on the vertical sprung acceleration of the sprung mass. It is calculated as follows:

1. Calculate the spectral density of the pavement roughness profile.
2. Multiply this spectral density by the square of the transfer function selected, to obtain the spectral density of the vertical sprung mass acceleration of the reference quarter-vehicle excited by the given roughness profile.
3. Calculate the integral of the spectral density of the vertical sprung mass acceleration over the full frequency spectrum and take the square root.

The resulting statistic has units of energy per unit mass per unit length of pavement traveled and represents the energy input from the road to the vehicle and vice-versa. This procedure was implemented into a PC-based computer software program called TRRI (Truck Response to Roughness Index).

INTRODUCTION

Historically, pavement serviceability has been defined in terms of the ride quality perceived by the traveling public (Carey et al, 1960). Ride quality has been considered to be a function of longitudinal pavement roughness. In the past 30 years, considerable efforts have been made in measuring pavement roughness as part of the data collected for pavement management purposes.

In 1982, the World Bank initiated an extensive study of the various pavement roughness measuring systems in order to develop a universal roughness index for describing the ride quality of passenger vehicles as perceived by the driver/passengers, (Sayers et al, 1986). This study distinguished two main categories of roughness measuring devices, namely response-type and profilometer-type. The roughness index proposed, referred to as the International Roughness Index (IRI), relates the passenger car ride quality to the accumulated displacement between the axle, (i.e., unsprung mass) and the body (i.e., sprung mass) of a passenger vehicle. To maintain universality, a computer model of a quarter-car was developed as the reference vehicle for calculating IRI. The IRI is reported in terms of the accumulated relative vertical displacement between sprung and unsprung masses per unit length traveled, in units of mm/km or inches/mile. The main advantage of the IRI is that it can be related to the output of either:

- response-type roughness measuring systems, (e.g., Mays-Ride Meter™, Car-Road Meters and so on) through regression or,
- profilometer-type roughness measuring systems, (e.g., Surface Dynamics Profilometer™, Dip Stick™ and so on) by directly inputting the profile measured into the quarter-car simulation software.

Clearly, the IRI is intended to reflect the pavement roughness attributes which affect the ride quality of passenger vehicles. There was some debate in the literature whether the accumulated vertical relative axle displacement is the best indicator of passenger car ride quality, (Janoff et al, 1985; McQuirt et al, 1986). Despite this criticism, the IRI has been widely accepted as the index of choice for reporting pavement roughness and it has been used extensively by North-American transportation agencies for pavement management purposes.

From this discussion, it is apparent that the IRI was not intended to describe the pavement roughness characteristics which affect heavy trucks. Indeed, the interaction between heavy trucks and pavements generates dynamic vehicle excitation which results in:

- dynamic axle loads affecting pavement damage and vehicle damage and,
- vertical vehicle accelerations affecting truck ride quality and cargo damage.

The extent of axle load variation due to vehicle dynamics can be quite substantial as demonstrated by a number of studies and summarized by a recent NCHRP report, (Gillespie et al, 1993). In general, the standard deviation of dynamic load increases with increasing vehicle speed and level of pavement roughness. Various suspensions exhibit different dynamic characteristics affecting the extent and frequency content of the axle loads generated. Extensive work has been done in evaluating the relative damaging effects of these dynamic loads on pavement deterioration, (e.g., Cebon et al 1987, Monismith et al 1988, Papagiannakis et al 1990, and so on). All these studies concluded that pavement damage increases with the amount of dynamic axle load variation. Also, some work was done in evaluating the effect of dynamic axle load excitation on the performance and service life of trucks, (Hu, 1987 and Sullivan, 1994). Little work is available on the effect of roughness on truck ride quality and cargo damage.

Clearly, the attributes of pavement roughness that affect heavy vehicle-pavement interaction are of interest to both the roadway authorities and the trucking industry. This aspect of pavement roughness needs to be studied and, if possible, a pavement roughness model developed which reflects this interaction. Furthermore, there is a need to develop a statistic for summarizing these pavement roughness attributes. The study at-hand addresses these needs by developing a roughness model and a summary statistic sensitive to the pavement roughness attributes affecting heavy vehicle-pavement interaction.

STUDY OBJECTIVES

The main objective of this study is to analyze pavement roughness in relation to the dynamic response of heavy vehicles and to develop a summary statistic tailored to describe this interaction. This paper offers a summary overview of this study which is fully documented by Gujarathi (1994). It focuses on:

- literature review of the most important studies in this area,
- analysis of experimental data on pavement roughness profile and dynamic axle loads obtained during an earlier experiment involving the instrumented vehicle developed by the National Research Council of Canada (NRCC), (Papagiannakis et al, 1990),
- study of the suitability of a quarter-vehicle model, similar to the quarter-car developed by the World Bank (Sayers et al, 1986), in simulating the observed pavement-vehicle interaction behavior and,
- identify a model response parameter suited to describe this interaction and develop a suitable summary statistic.

LITERATURE REVIEW

Gillespie et al, (1980) conducted an NCHRP-funded study dealing with the calibration of response-type roughness measuring devices. A number of calibration reference alternatives were considered, namely use of a shaker device, "standard" pavement sections and actual pavement elevation profile measurements. The latter was chosen as a more direct approach in conjunction with a quarter-car simulation. The differential equations governing the motion of the quarter-car are shown below:

$$\ddot{Z}_s M_s + C_s(\dot{Z}_s - \dot{Z}_u) + K_s(Z_s - Z_u) = 0 \qquad (1)$$

$$-\ddot{Z}_s M_s + M_u \ddot{Z}_u + K_t (Z_u - Z) = 0 \tag{2}$$

where, M_s and M_u are the sprung and usprung masses, K_s and K_t are the elastic constants for the suspension and the tire and C_s is the damping constant for the suspension. The configuration of the quarter car is shown in Figure 1, where Z_s and Z_u are the vertical displacements of the sprung and unsprung masses, respectively.

Vehicle Parameters	K_t/M_s	K_s/M_s	M_u/M_s	C_s/M_s
HSRI	667	62.3	0.150	6.0
BPR	667	133.3	0.167	5.0

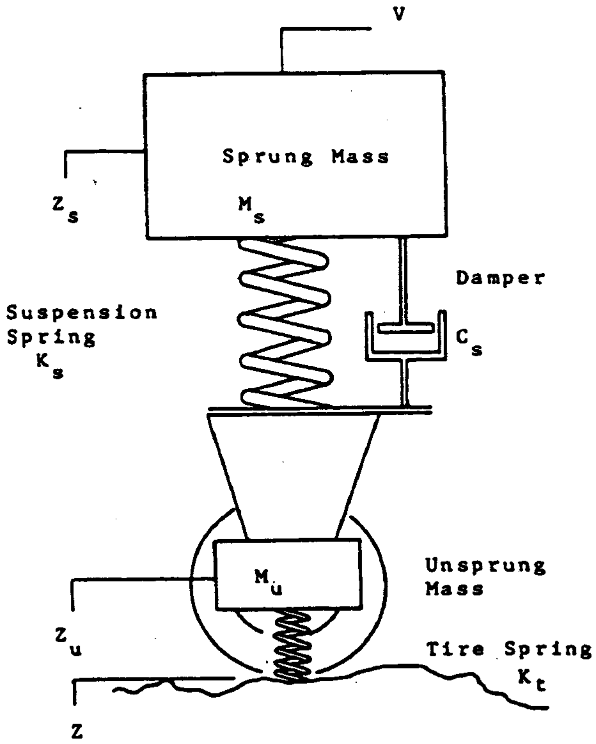

Figure 1: Quarter-Car Simulation, (After Gillespie at al, 1980)

The contribution of the pavement roughness profile and the quarter-car mechanical properties to vehicle response were extensively studied through the use of transfer functions, (Figure 2). Clearly, the quarter-car simulation is sensitive to excitation frequencies of 1 and 10 Hz. The study proposed the use of the average rectified velocity (*ARV*) as the calibration reference, (Equation 3).

$$ARV = \frac{1}{T}\int_{0}^{T} \left| \dot{Z}_s - \dot{Z}_u \right| dt \tag{3}$$

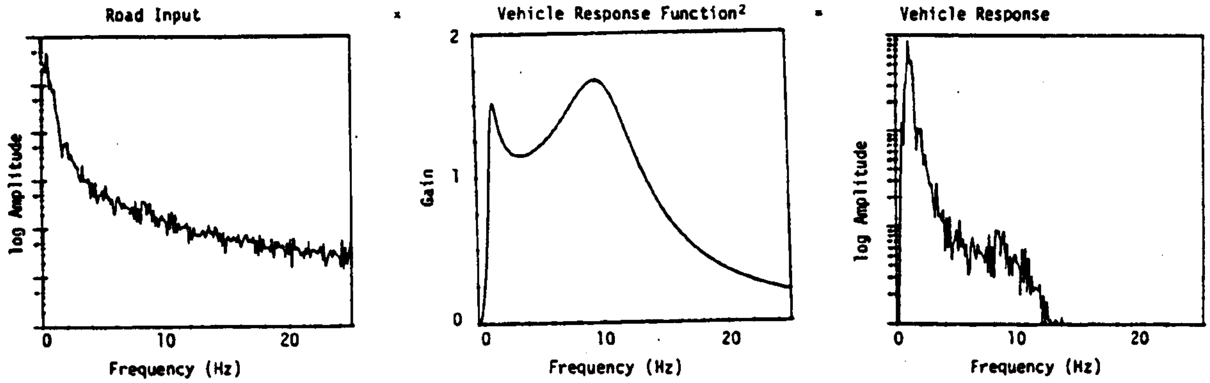

Figure 2: Contribution of Vehicle and Road Input to the Spectral Density of the Relative Axle-Body Displacement, (After Gillespie et al, 1980).

where, T is the time required to traverse a section of road and Z_s and Z_u are the displacements of the sprung and unsprung masses of the quarter-car simulation. *ARV* is in essence the accumulated vertical displacement between the sprung and unsprung masses which makes it compatible with the readings of conventional response-type measuring devices.

Hudson et al, (1985) proposed an alternative pavement roughness statistic, referred to as the Root Mean Vertical Acceleration (*RMSVA* or *VA*). This is a function of the pavement profile geometry only, defined as:

$$VA_b = c\left[\sum_{i=k+1}^{n-k} \frac{(S_b)_i^2}{n-2k}\right]^{1/2} \tag{4}$$

where,

VA_b = root mean square vertical acceleration corresponding to the base length b,
$(S_b)_i$ = second derivative of the pavement elevation Y at point i (Equation 5),
s = the horizontal distance between adjacent points, called sample interval,
k = arbitrary integer used to define base length b as a multiple of s,
n = total number of elevation points and,
c = a constant required for unit conversion from a spatial acceleration to a frequency domain acceleration.

$$(S_b)_i = \frac{Y_{i+k} + Y_{i-k} - 2Y_i}{ks^2} \qquad (5)$$

The study compared the *VA* to the *ARV* statistic proposed by Gillespie et al (1980) and a variation of this statistic, referred to as the average rectified slope (*ARS*) defined as:

$$ARS = \frac{1}{L}\int_0^T \left| \dot{Z}_s - \dot{Z}_u \right| dt \qquad (6)$$

where, L is the length of a section of road over which the statistic is calculated. Regression equations were developed between the Mays-Ride-Meter readings *MO* (*inches/mile*) and the *VA* statistics ($feet/\sec^2$), exhibiting a very good fit:

$$MO = -20 + 23VA_4 + 58VA_{16}, \quad (R^2 = 0.96) \qquad (7)$$

An extensive sensitivity analysis of the *VA*, *ARV* and *ARS* statistics was undertaken. Both simulated profiles and actual profiles were used. Three types of artificial profiles were used, namely a sinusoidal, a "saw-tooth" and a rectangular. Their frequency and amplitude was varied and the resulting effect to the calculated statistics evaluated. The actual pavement profile data was measured with a Surface Dynamics Profilometer™. The stability of the calculated statistics was tested by varying the sampling interval.

This study also examined the sensitivity of the *ARV* and *ARS* statistics to the frequency of the pavement roughness input. Subjective data on vertical acceleration tolerance (Goldman 1948) were used to establish "isocomfort" curves, (Figure 3). Pavement roughness amplitudes were established corresponding to these isocomfort curves using the quarter car simulation developed by Gillespie, (1980), (Figure 4). It was suggested that the minimum amplitude exhibited at about 10 Hz was a shortcoming of the quarter-car related statistics because, "for a given amplitude, the roughness statistic should vary in direct proportion to the frequency of the wave forms". It was therefore concluded that the *VA* is a preferable statistic compared to either the *ARV* or the *ARS*.

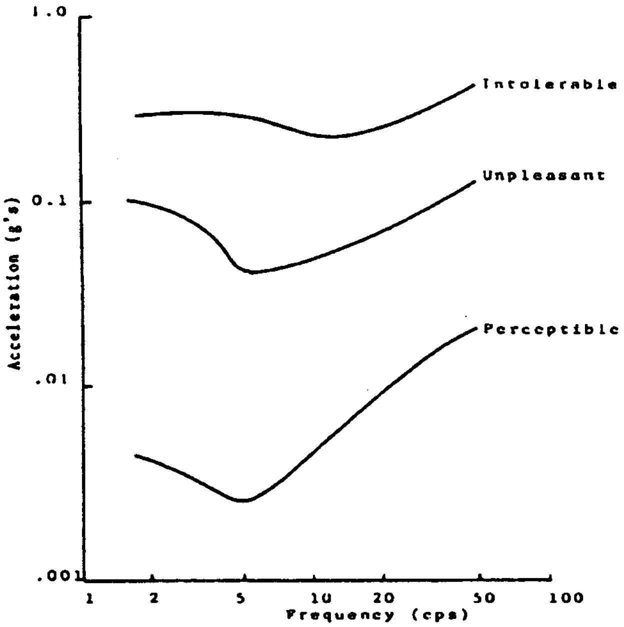

Figure 3: Subjective Tolerance Levels for Vertical Acceleration, (After Goldman, 1948)

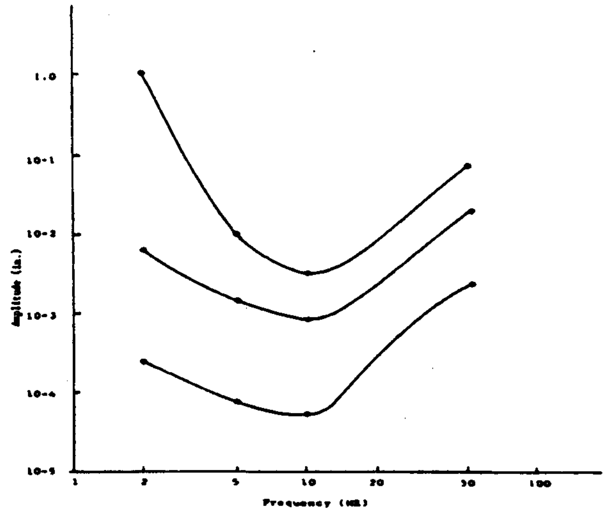

Figure 4: Amplitudes corresponding to Isocomfort Curves in Fig. 3, (After Hudson et al, 1985).

Wambold, (1985) offered an overview of the fundamentals of pavement-vehicle interaction utilizing simple vehicle models. Quarter-car, half-car and quarter-truck models were analyzed. Transfer functions were developed indicating the relationship between the desired vehicle output, (e.g., accumulated sprung-unsprung mass displacement) and the input variable, (i.e., roughness elevation profile) as a function of input variable frequency. Examples of transfer functions are shown in Figures 5 and 6 for the relative displacement between the sprung and unsprung masses and the tire load of a quarter-truck, respectively. Note that the relative displacement between the sprung and unsprung masses of a quarter-car is comparable to the *ARV* statistic described earlier, (Equation 3).

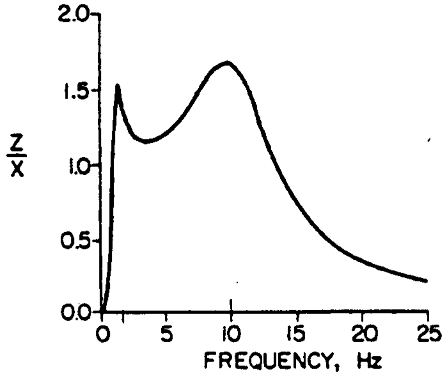

Figure 5: Transfer Function Sprung Mass minus Unsprung Mass Displacements versus Roughness Amplitude, (After Wambold et al, 1985).

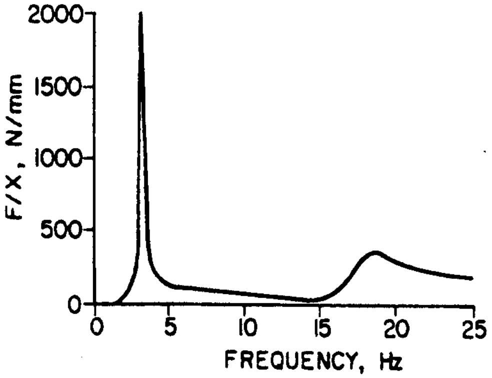

Figure 6: Transfer Function of Tire Load versus Roughness Amplitude for a Quarter-Truck, (After Wambold et al, 1985).

It was concluded that the dominant pavement roughness excitation frequencies affecting the quarter-car are different than the frequencies affecting dynamic tire loads.

The World Bank, (1986a and 1986b) conducted a large scale experimental evaluation and correlation of the variety of pavement roughness measuring systems. The intention was to arrive at a universal pavement roughness index which would be stable in time and transferable between jurisdictions. The reference average rectified slope of the quarter-car initially proposed by Gillespie et al (1980) was recommended as the universal index. This is in essence the *ARS* defined earlier (Equation 6), and was referred to as the International Roughness Index (IRI). The IRI was calculated through a computer simulation of a quarter-car such as the one shown in Figure 1 traveling at 80 km/h. The computer simulation used a state transition matrix approach for solving the four simultaneous linear differential equations defining the motion of the quarter-car. The roughness profile was smoothened through a moving average algorithm to account for tire enveloping, and then it was input into the quarter-car simulation. Two alternative approaches were considered for handling the input of the roughness profile for the two wheel paths:

- average them and then input the average into the quarter-car model or,

- input the left and right path roughness profiles into a half-car simulation model consisting of two coupled quarter-car models having two degrees of freedom, (i.e., bounce and yaw). The *resulting* statistic is referred to as the Half-Car Roughness Index (HRI).

Todd et al, (1989) developed dynamic simulation computer models for three truck configurations, namely a quarter-truck model, a half single-unit 2-axle truck model and a half 5-axle semi-trailer truck model. The objective of the study was to predict ride quality and pavement loading as well as to arrive at proper mechanical characteristics for these vehicle models.

The quarter-truck model developed is shown in Figure 7. The differential equations describing its motion are identical to Equations 1 and 2 described earlier. Their expanded form is given next, (i.e., Equations 8 to 11), following the notation of Figure 7.

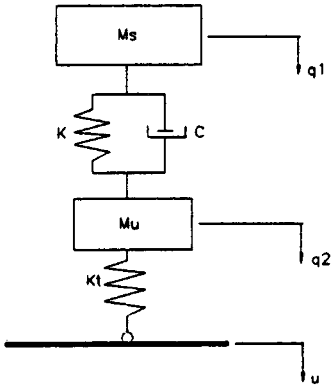

Figure 7: Quarter-Truck Model, (After Todd et al, 1989)

$$\dot{q}_1 = q_3 \tag{8}$$

$$\dot{q}_2 = q_4 \tag{9}$$

$$\dot{q}_3 = \left[\left(-q_1 K + q_2 K - q_3 C + q_4 C\right)\right]/M_s \tag{10}$$

$$\dot{q}_4 = \left[\left(q_1 K - q_2 (K_t + K) + q_3 C - q_4 C + uK_t\right)\right]/M_u \tag{11}$$

The mechanical constant values used in the quarter truck simulation are listed in Table 1.

Table 1:
Mechanical Constants of Quarter-Truck Model
(After Todd et al, 1989)

Symbol	Variable	Value Selected
M_s	Sprung mass	22.9036 $\mathrm{lbsec^2/in}$
M_u	Unsprung mass	2.976 $\mathrm{lbsec^2/in}$
K	Suspension elastic const.	6500. lb/in
C	Suspension damping const.	15. lbsec/in
K_t	Tire elastic const.	5000. lb/in

In a similar fashion, the formulation of the other two truck models treated suspension systems as combinations of linear springs and dash-pots, while tires were modeled as linear springs. The formulation for these models was more complex, having 2 and 4 degrees of freedom, respectively. For all three models, a 4th-order Runge-Kutta algorithm was used for solving the simultaneous differential equations involved. These models were then tested using two types of road profiles:

- a simulated sinusoidal profile to determine frequency responses and,
- several actual road profiles to calculate summary statistics of vehicle responses.

For the latter, two statistics were proposed, namely, the Root Mean Square (*RMS*) of the vertical acceleration of the sprung mass and the Dynamic Impact Factors (*DIF*) of the dynamic axle loads, (i.e., Equations 12 and 13, respectively).

$$RMS = \left[\left(\frac{1}{N}\sum_{i=1}^{N} a_i^2\right)\right]^{1/2} \tag{12}$$

where,
a_i = acceleration of the sprung mass at the *i*th time step and,
N = number of observations.

$$DIF = \left(\frac{\left[\sum_{i=1}^{N} (F_i - F)^2 \right]}{(N-1) * F^2} \right)^{1/2} \qquad (13)$$

where,

F_i = tire force at the ith time step and,

F = mean tire force.

These two quantities were related to ride comfort and pavement damage, respectively. Transfer functions were presented for the dynamic axle load of the 2-axle truck model versus the amplitude of the sinusoidal profile, (Figure 8). The study concluded that the quarter-truck model yielded higher sprung mass *RMS* values and dynamic load *DIF* factors than the 2-axle and the 5-axle truck models.

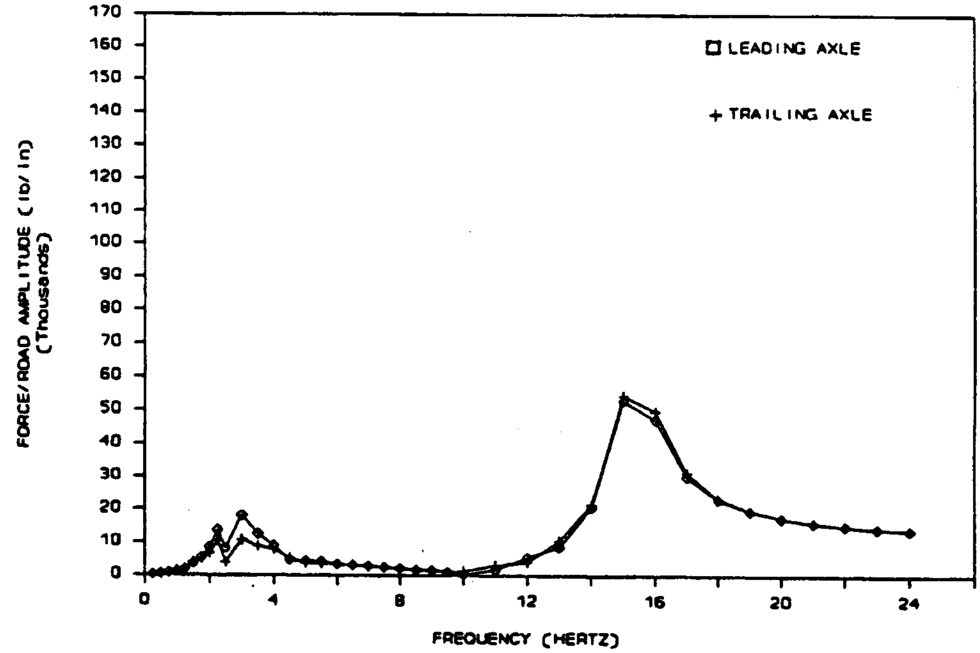

Figure 8: Transfer Function of Dynamic Tire Load versus Pavement Roughness Profile, (After Todd et al, 1989).

ANALYSIS FRAMEWORK

The earlier discussion identified two vehicle response parameters of interest in studying heavy vehicle-pavement interaction:

- the dynamic axle loads generated at the tire/pavement interface, which affect pavement damage and vehicle damage and,
- the vertical sprung mass acceleration of the vehicle, which affects both the ride quality and the damage of the cargo.

Hence, the proposed pavement roughness model and summary statistic must reflect these two heavy vehicle response parameters. The following sections explore the relationship between pavement roughness profile and these two vehicle response parameters using both experimental data and simulated data obtained with a quarter-truck model.

Analysis of the Experimental Data

The experimental data was obtained with the instrumented vehicle developed by the NRCC, (Papagiannakis et al 1990). The instrumentation included strain gauges and accelerometers located on the axles yielding dynamic axle load, as well as accelerometers located on the body of the vehicle. Data was obtained on 5 pavement sections of increasing roughness, (i.e., Site 1, Site 2 and so on) at 3 vehicle speeds, (i.e., 40, 60 and 80 *km/h*). The vehicle was equipped with an air suspension in the drive axles and a rubber suspension in the trailer axles. Pavement roughness was measured at intervals of 0.15 *m*, (i.e., 6 inches) using a Surface Dynamics Profilometer™. An axle detector was used to provide accurate spatial reference for the vehicle.

The data was analyzed by means of transfer functions between the vehicle response parameters of interest and the pavement roughness excitation input. Figures 9 and 10 show transfer functions for dynamic axle load for Sites 1, 3 and 5, for the rubber suspension and the air suspension, respectively, at a speed of 80 km/h. Figure 9 shows clearly that regardless of roughness level, the rubber suspension is sensitive to excitation frequencies of about 3.5 and 12.5 Hz. This trend is repeated, in a less obvious fashion, for the air suspension. The "noise" that appears on Site 1 is due to the tire eccentricity (i.e., at 22.2 m/sec (80 km/h) a tire with a radius of 0.57 meter has a circumference of 3.6 meters, which results in a load excitation frequency of about 6 Hz). At low roughness levels, this source of excitation can contribute substantially to the dynamic load variation observed.

Figure 11 shows the transfer function of the vertical acceleration at the rear of the trailer versus the pavement roughness excitation input. Clearly, the vertical sprung mass acceleration is sensitive to the same 3.5 Hz excitation frequency identified earlier. Note that for a vehicle speed of 22.2 m/sec, the 3.5 Hz excitation frequency corresponds to a pavement roughness wavelength of about 6.3 meters, (i.e., 21 feet). This sensitivity to the 3.5 Hz pavement roughness excitation frequency remains relatively unchanged as the vehicle speed changes, (Figure 12). It is evident that the acceleration of the sprung mass contributes significantly to the dynamic axle load variation observed. Hence, this is the single most important vehicle response parameter related to both aspects of heavy vehicle-pavement interaction, namely pavement/vehicle damage and ride quality/cargo damage. Clearly, the pavement roughness model needed should reflect the vertical sprung mass acceleration response of heavy vehicles. Furthermore, it should exhibit a dynamic behavior similar to the one experimentally observed. As explained next, a simple quarter-vehicle model was developed for this purpose.

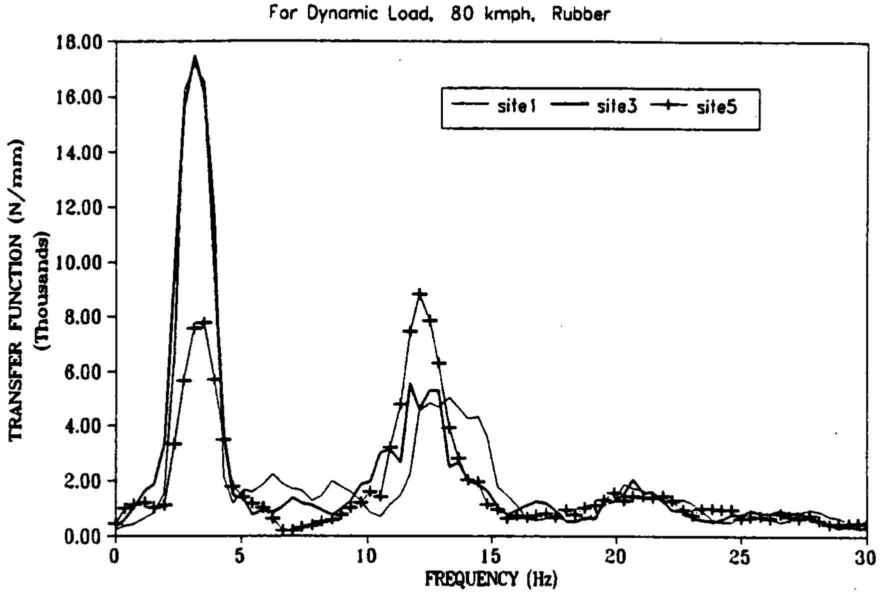

Figure 9: Transfer Function of Dynamic Load versus Profile Elevation Difference; Rubber Suspension at 80 *km/h*.

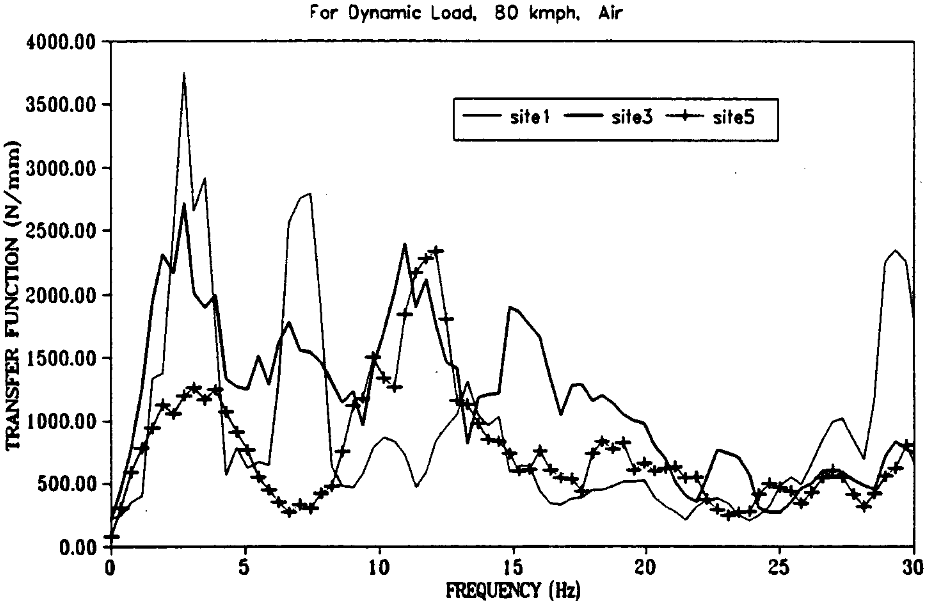

Figure 10: Transfer Function of Dynamic Load versus Profile Elevation Difference; Air Suspension at 80 *km/h*.

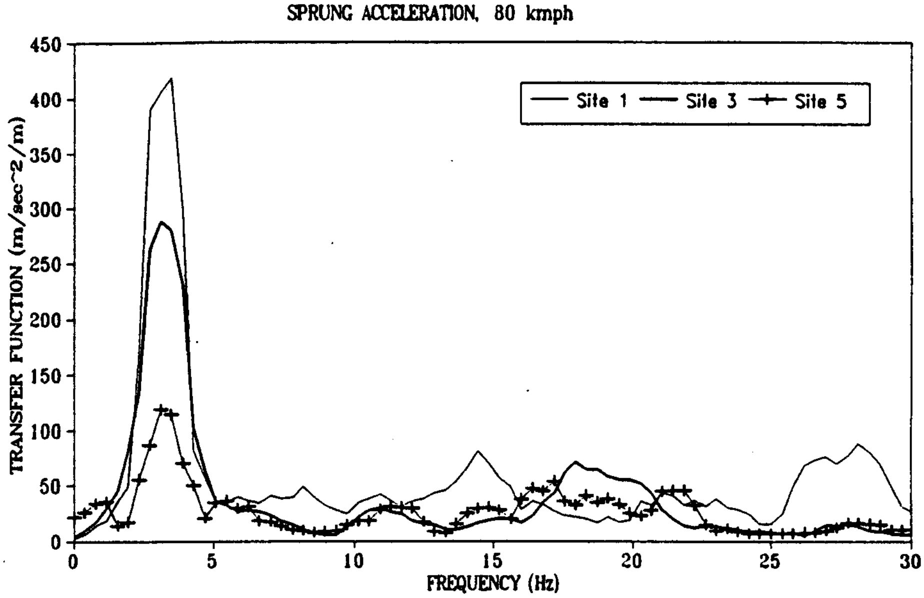

Figure 11: Transfer Function of Vertical Sprung Mass Acceleration versus Profile Elevation Difference at 80 km/h.

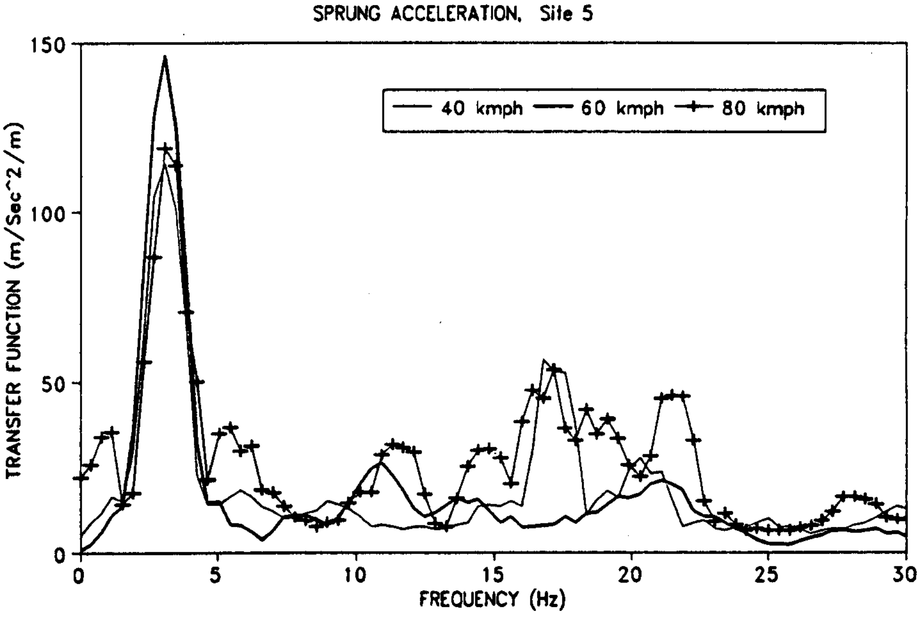

Figure 12: Transfer Function of Vertical Sprung Mass Acceleration versus Profile Elevation Difference for Site 5.

Analysis of the Quarter-Vehicle Simulation Data

A simple quarter-vehicle model was developed by numerically solving the four differential equations described earlier, (Equations 8 to 11). The equations were solved through an Adams-Moulton/Gear algorithm using subroutines from the IMSL software library (IMSL 1991) in the PC environment. The model provided for smoothing of the pavement elevation profile through a moving average technique to account for tire enveloping. It also allowed variable input of the mechanical constants of the vehicle.

The first quarter-vehicle model tested had mechanical constants identical to the quarter-car used as the reference vehicle for calculating the IRI, (World Bank, 1986a and 1986b). The transfer functions for the *ARS* statistic and the vertical sprung mass acceleration versus the pavement roughness excitation input are shown in Figures 13 and 14, respectively. Figure 13 shows clearly that the *ARS* is sensitive mainly to excitations frequencies of 1.5 Hz. This suggests that the IRI is not suitable as a roughness index reflecting the dynamic observed behavior of heavy trucks as described earlier. Furthermore, Figure 14 suggests that the sprung mass acceleration of the quarter-car is sensitive to excitation frequencies of 1.5 and 11 Hz which is inconsistent with observed behavior. Hence, the quarter car simulation seems to be unsuitable for modeling the roughness attributes which affect heavy vehicle-pavement interaction.

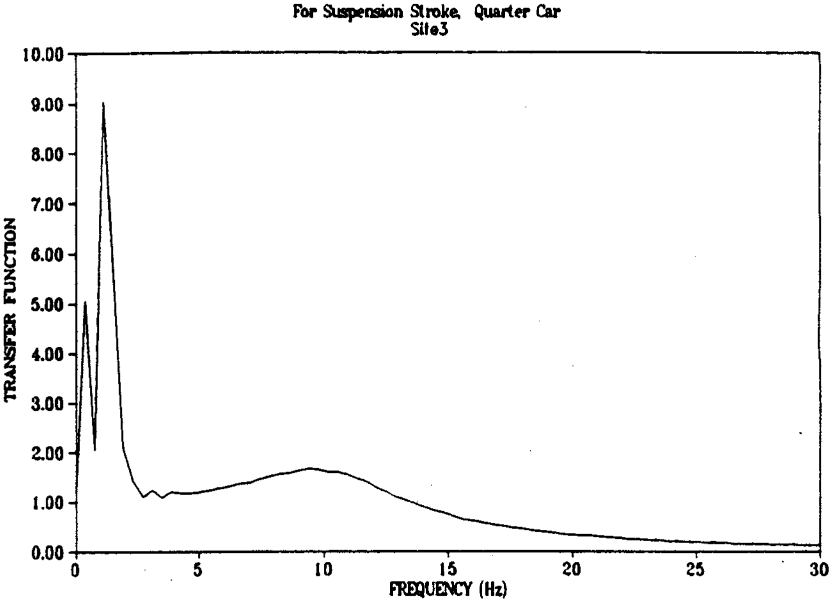

Figure 13: Transfer Function of the *ARS* versus the Profile Elevation Difference; Quarter-Car Model at 80 km/h, (Site 3).

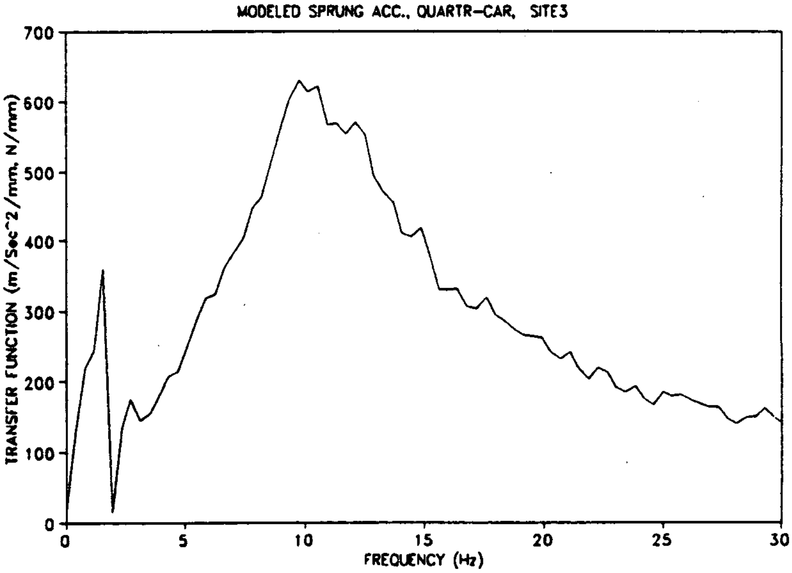

Figure 14: Transfer Function of Vertical Sprung Mass Acceleration versus Profile Elevation Difference; Quarter-Car Model at 80 km/h, (Site 3).

The second quarter-vehicle tested had the mechanical properties of the quarter-truck described by Wambold, (1985). These are summarized below.

Table 2:
Mechanical Constants of the Quarter-Truck
Expressed as Ratios of the Sprung Mass, (After Wambold, 1985)

Mechanical Constant	**Ratio**	**Value**
Suspension elastic const.	K / M_s	118 1 / sec^2
Tire elastic constant	K_t / M_s	755 1 / sec^2
Unsprung mass	M_u / M_s	0.146
Suspens. damping const.	C / M_s	4.7 1 / sec

Figure 15 shows the transfer function of the sprung mass acceleration of this quarter-truck versus the pavement roughness excitation input. The effect of the mechanical constants of this quarter-vehicle on the sprung mass acceleration transfer function was explored as shown in Figure 16. It can be seen that the constants resulting in a transfer function similar to the one observed with the instrumented NRCC vehicles are similar to the ones used by Wambold (1985) with the exception of the elastic tire constant which should be considerably lower, (i.e., K_t / M_s= 200 1 / sec^2). The selected quarter-vehicle constants are shown in Table 3. These mechanical constants are selected to describe a quarter-vehicle to be used as a reference in arriving at a summary pavement roughness statistic as described next.

Developing a Pavement Roughness Summary Statistic

The earlier discussion established that the vertical acceleration of the sprung mass of a vehicle is the response parameter of interest in describing heavy vehicle-pavement interaction. Furthermore, it demonstrated that a quarter-vehicle model with suitable mechanical constants can exhibit a dynamic response similar to the one observed experimentally.

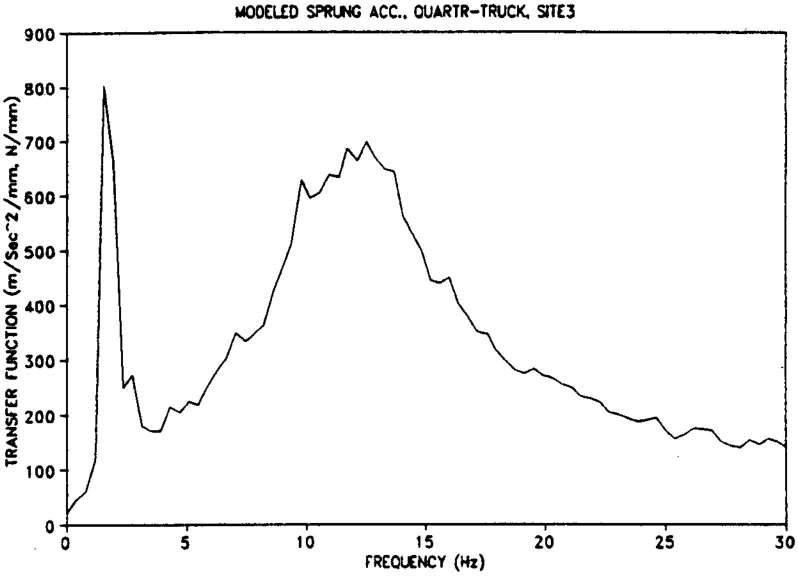

Figure 15: Transfer function of the Sprung Mass Acceleration versus Profile Elevation Differ.; Quarter-Truck Model at 80 km/h, (Site 3).

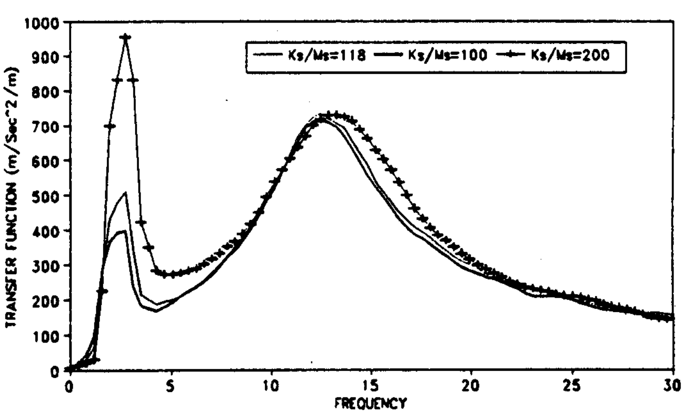

Figure 16: Effect of the Mechanical Constants of the Quarter-Vehicle on the Transfer Function of the Sprung Mass Acceleration versus Profile Elevation Differ., (Site 3).

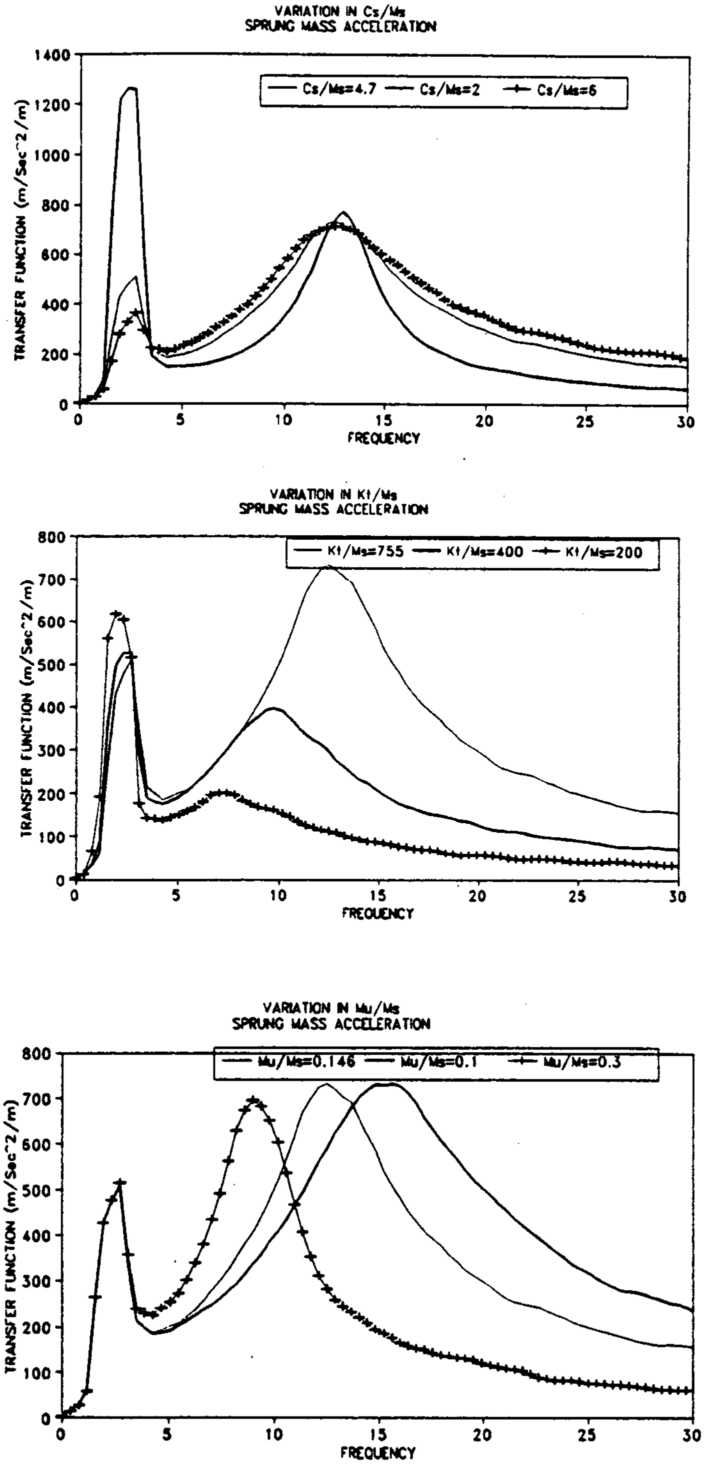

Figure 16, (Cont.): Effect of the Quarter-Vehicle Constants the Transfer Function of the Sprung Mass Acceleration versus Profile Elevation Differ., (Site 3).

Table 3:
Selected Mechanical Constants of the Quarter-Vehicle,

Mechanical Constant	**Ratio**	**Value**
Suspension elastic const.	K / M_s	118 1 / sec^2
Tire elastic constant	K_t / M_s	200 1 / sec^2
Unsprung mass	M_u / M_s	0.146
Suspens. damping const.	C / M_s	4.7 1 / sec

This response is best described by the transfer function of the vertical sprung mass acceleration with respect to the pavement roughness profile excitation. It was also known that the spectral density of the sprung mass acceleration of a vehicle driving over a known pavement roughness profile can be calculated as the product of the sprung mass acceleration transfer function multiplied by the square of the spectral density of the profile, (Figure 2).

Futhermore, integration of the resulting spectral density over all the frequencies of excitation results in a statistic which is indicative of the mean square of the accumulated vertical sprung mass acceleration over the entire length of the section, (Bendat et al, 1980). This statistic has units of energy per unit sprung mass per unit length of pavement traveled and represents the energy input from the road to the vehicle and vice-versa. For a particular pavement section the roughness statistic depends only on the transfer function selected as reference and hence, it is universal and stable.

IMPLEMENTATION

The following steps are involved in calculating the pavement roughness index described herein:

1. Obtain the pavement roughness profile output from the WS DOT South Dakota Profilometer.

2. Calculate the average elevation for the right and left wheel paths and produce an ASCII file with the average profile elevation in inches.
3. Calculate the difference in elevation between successive points in 1/1000 of an inch.
4. Compute the spectral density of the profile elevation difference data.
5. Multiply this spectral density by the square of the transfer function supplied in file TRANSFUN.DAT, to obtain the spectral density of the vertical sprung mass acceleration of the reference quarter-vehicle excited by the given roughness profile.
6. Calculate the integral of the spectral density of the vertical sprung mass acceleration over the full frequency spectrum and take the square root.

Steps 1 and 2 are to be performed by WS DOT personnel. Steps 3 to 6 are performed through a PC-based program developed for this purposed, which was named TRRI (Truck Response to Roughness Index). The result is in terms of accumulated sprung mass acceleration per unit mass over the length of a section ($m/\sec^2/km$) and it is indicative of the energy per unit mass exchange between the vehicle and the pavement. A typical example of the output of the program is given in Table 4 for five sites of increasing roughness, where Site 1 is a new asphalt concrete pavement and Site 5 is an asphalt concrete pavement scheduled for overlaying.

Table 4:
Example Output of the TRRI Model

Site Number	**Accumulated Vertical Sprung Mass. Accel.** $m/\sec^2/km$ $*10^6$
1	0.17
2	0.30
3	0.38
4	0.41
5	0.54

CONCLUSIONS

This study presented a roughness model describing the pavement roughness attributes affecting heavy vehicle-pavement interaction. Dynamic vehicle response data from two sources was analyzed, namely experimental data obtained with the instrumented vehicle developed by the NRCC and simulated data obtained with a quarter-vehicle simulation.

It was found that the vehicle response parameter of interest in this interaction is the sprung mass vertical acceleration because it relates to both pavement/vehicle damage as well as to ride quality/cargo damage. This was demonstrated by analyzing the transfer functions of both the dynamic axle load and the vertical sprung mass acceleration over a range of pavement roughnesses and vehicle speeds. The vertical sprung mass acceleration transfer function showed a distinct sensitivity to pavement roughness excitation frequencies of 3.5 Hz.

A pavement roughness statistic was proposed based on the reference vertical sprung mass acceleration transfer function obtained from the quarter-vehicle simulation. The square of this transfer function is to be multiplied by the spectral density of the profile to yield the spectral density of the vertical sprung mass acceleration, which is in turn to be integrated over the full range of frequencies. The pavement roughness statistic, called the TRRI, is obtained as the square root of the integral and has units of acceleration per unit mass and length. It is indicative of the energy exchange between the pavement and the vehicle.

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APPENDIX A

Development of a Quarter-Car and a Quarter-Truck model:

The following figure illustrates the mechanical model of the quarter-vehicle with the variables defined below it. The equations of motion describing the quarter-vehicle are developed by drawing the free body diagrams of sprung and unsprung masses and analyzing the various forces acting on it.

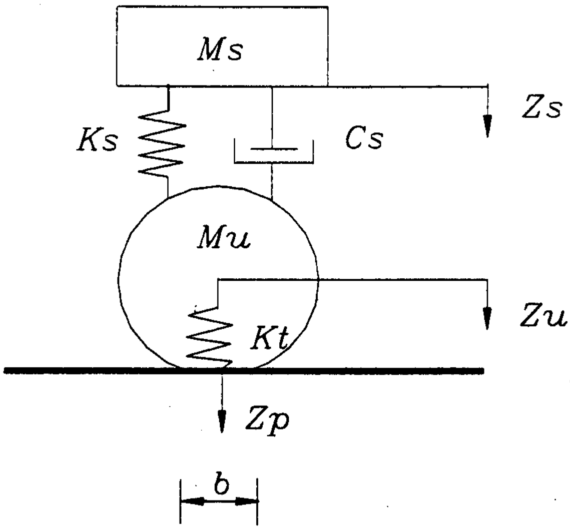

Figure A-1: Quarter-Vehicle Model

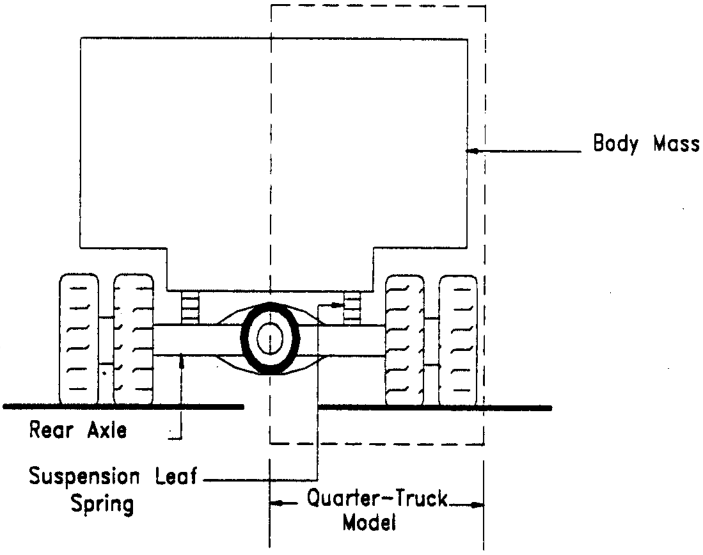

Figure A-2: Outline of Quarter-Vehicle Model

Where the variables describing the quarter-Vehicle are,

M_s = Sprung mass (frame)

M_u = Unsprung mass (tire)

K_s = Suspension spring constant

K_t' = Tire spring constant

C_s = Suspension damping constant

Z_p = Profile input

b = Base length

Figure A-3 below shows the free body diagram of sprung mass with the various forces acting on it

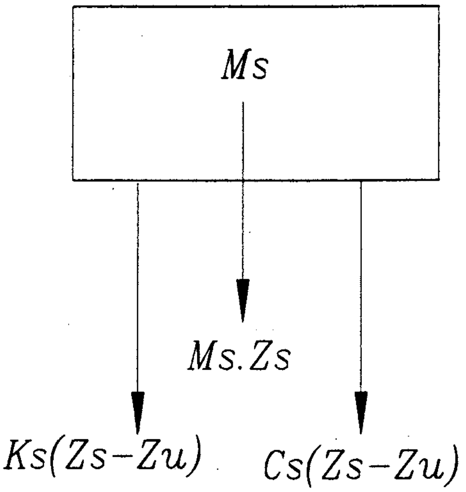

Figure A-3: Free body Diagram of Sprung Mass

Taking the equilibrium in Y direction of Cartesian coordinate axes,

$$\sum Fy = 0 = M_s \ddot{Z}_s + C_s(\dot{Z}_s - \dot{Z}_u) + K_s(Z_s - Z_u) = 0 \qquad \text{(A-1)}$$

This equation describes the equation of motion of a sprung mass of a quarter-car or quarter-truck.

Figure A-4 below shows the free-body diagram of an unsprung mass of a vehicle.

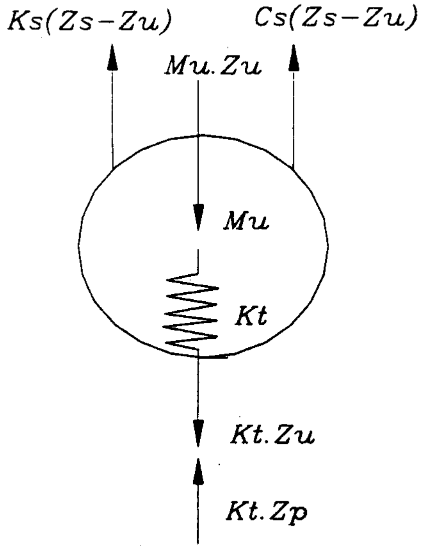

Figure A-4: Free Body Diagram of Unsprung Mass.

Taking equilibrium in Y direction, we get,

$$\sum Fy=0$$

$$M_u\ddot{Z}_u - K_s(Z_s - Z_s) - C_s(\dot{Z}_s - \dot{Z}_u) + K_t Z_u - K_t Z_p = 0$$

$$M_u\ddot{Z}_u + M_s\ddot{Z}_s + K_t Z_u - K_t Z_p = 0 \qquad \text{(A-2)}$$

Let:

$$Z_s = Z_1$$

$$Z_u = Z_2$$

$$\dot{Z}_s = Z_3$$

$$\dot{Z}_u = Z_4$$

Using these notations equations (A-1) and (A-2) will become:

$$M_s\dot{Z}_3 + C_s(Z_3 - Z_4) + K_s(Z_1 - Z_2) = 0 \qquad \text{(A-3)}$$

$$M_s\dot{Z}_3 + M_u\dot{Z}_4 + K_t Z_2 - K_t Z_P = 0 \qquad \text{(A-4)}$$

From equation (A-3) and (A-4), following equations are obtained.

$$\dot{Z}_3 = (-K_s Z_1 + K_s Z_2 - C_s Z_3 + C_s Z_4) / M_s \qquad \text{(A-5)}$$

$$\dot{Z}_4 = (K_s Z_1 - (K_t + K_s) Z_2 + C_s Z_3 - C_s Z_4 + K_t Z_p) / M_u \qquad \text{(A-6)}$$

The four equations describing Quarter-Vehicle Model can now be written as:

$$\dot{Z}_1 = Z_3 \tag{A-7}$$

$$\dot{Z}_2 = Z_4 \tag{A-8}$$

$$\dot{Z}_3 = (-K_s Z_1 + K_s Z_2 - C_s Z_3 + C_s Z_4) / M_s \tag{A-9}$$

$$\dot{Z}_4 = (K_s Z_1 - (K_t + K_s) Z_2 + C_s Z_3 - C_s Z_4 + K_t Z_p) / M_u \tag{A-10}$$

The constants for quarter car for the International Road and Roughness Experiment (IRRE) are:

Ks/Ms = 62.3 $\sec^{-2}$

Kt/Ms = 653 $\sec^{-2}$

Mu/Ms = 0.150

Cs/Ms = 6.0 $\sec^{-1}$

Putting these constants the quarter car model is described as:

$$\dot{Z}_1 = Z_3 \tag{A-11}$$

$$\dot{Z}_2 = Z_4 \tag{A-12}$$

$$\dot{Z}_3 = -62.3 Z_1 + 62.3 Z_2 - 6.0 Z_3 + 6.0 Z_4 \tag{A-13}$$

$$\dot{Z}_4 = 415.33 Z_1 - 4768.667 Z_2 + 40.0 Z_3 - 40.0 Z_4 + 4353.33 Z_p \tag{A-14}$$

The values of the four variables Z_1 to Z_4 at time t=0 (initialization) for quarter-car can be written as:

$Z_1(0)$ = Ms.g / Ks = 0.1574638

$Z_2(0)$ = (Ms+ Mu).g / Kt = 0.00172764

$Z_3(0)$ = 0.0

$Z_4(0)$ = 0.0

Replacing these constants describing the quarter-car by the constants describing the quarter-truck the equations of motion describing quarter-truck can be obtained.. Below are shown the constants describing quarter-truck [NCHRP 105]

Ks/Ms = 118.0 $\sec^{-2}$

Kt/Ms = 755.0 $\sec^{-2}$

Mu/Ms = 0.146

Cs/Ms = 4.7 sec^{-1}

APPENDIX B

A FORTRAN program calling subroutines from IMSL software, describing quarter-truck model.

```
c ***************************************************************************
c *  This program should be linked with IMSL                                *
c *                                                                         *
c *   This program solves the quarter-truck  model.                         *
c *   It solves the system of one-dimensional differential equations       *
c *   describing quarter-truck, by using IMSL subroutine IVPAG.             *
c *   This subroutine uses Adams-Moulton/Gear Method of Numerical           *
c *   Integration.                                                          *
c *   The Basic Equations describing the quarter-truck are:                 *
c *   ..           .  .                                                     *
c *   Zs Ms + Cs(Zs-Zu) + Ks(Zs-Zu) = 0  and                                *
c *   ..          ..                                                        *
c *   Zs Ms + Mu Zu + Kt(Zu-Z) = 0                                          *
c *                                                                         *
c *   Where Z          = Elevation of the roughness profile                 *
c *       Ms and Mu = Sprung and unsprung masses                            *
c *       Ks and Cs  = Elastic and damping suspension constants             *
c *       Kt              = Tire elastic constant                           *
c *                                                                         *
c *   The constants used in describing quarter-truck are:                   *
c *                                                                         *
c *   Ks/Ms   = 118 /sec^2    Mu/Ms   = 0.146                               *
c *   Kt/Ms   = 755 /sec^2    Cs/Ms   = 4.7 /sec                            *
c *                                                                         *
c *   The user can use above given constants or can supply other            *
c *   constants also. The program does ask about this option.               *
c *                                                                         *
c *   The program asks the user to input:                                   *
c *   # Input filename, which consists of the difference in the             *
c *     profile elevation points. These are in 100th of an inches.          *
c *                                                                         *
c *   # Mechanical constants, if user wants to supply different             *
c *     than default values.    and,                                        *
c *                                                                         *
c *   # Choice of the variable, which includes:                             *
c *                                                                         *
c *    * Relative displacement of sprung and unsprung masses                *
c *    * Sprung mass vertical acceleration                                  *
c *    * The modeled dynamic load generated by the vehicle on the road      *
```

```
c *                                                                          *
c ****************************************************************************



      INTEGER NEQ, NPARAM
      PARAMETER (NEQ=4, NPARAM=50,NDIM=5000)
C
      COMMON ATA(NDIM),IDUM
C
      COMMON P1,P2,P5,P6,P7,P8

      INTEGER IDO, IMETH, INORM, NOUT,MXSTEP
      REAL A(1,1),FCN,FCNJ,HINIT,PARAM(NPARAM),TOL,X,XEND,Y(NEQ)
      REAL B,C
C
      EXTERNAL FCN, IVPAG, SSET, UMACH

      CHARACTER*20 FIN
      CHARACTER*20 FOUT

      WRITE(*,*) 'PLEASE WRITE THE INPUT FILENAME'
      READ(*,'(a)')FIN
      WRITE(*,*) 'PLEASE WRITE THE OUTPUT FILENAME'
      READ(*,'(a)')FOUT

      OPEN(UNIT=8,FILE=FIN)

      OPEN(UNIT=11,FILE=FOUT)

      WRITE(*,5)
 5    FORMAT(/////)
 6    FORMAT(//)
      WRITE(*,*) 'PLEASE ENTER ONE OF THE FOLLOWING'
      WRITE(*,6)

      WRITE(*,*)'1:    TO USE BUILT IN MECHANICAL CONSTATNS'
      WRITE(*,*)'2:    TO DEFINE YOUR OWN CONSTATNS'
      READ(*,*)UCON

      IF(UCON.NE.1)THEN
      WRITE(*,5)
      WRITE(*,*)'PLEASE ENTER Ks/Ms VALUE'
      READ(*,*)P1
```

```
      WRITE(*,*)'PLEASE ENTER Kt/Ms VALUE'
      READ(*,*)P4
      WRITE(*,*)'PLEASE ENTER Mu/Ms VALUE'
      READ(*,*)P3
      WRITE(*,*)'PLEASE ENTER Cs/Ms VALUE'
      READ(*,*)P2
      WRITE(*,*)'PLEASE ENTER VALUE OF SPRUNG MASS IN POUNDS'
      READ(*,*)P20
      ENDIF

      WRITE(*,5)
      WRITE(*,*) 'PLEASE ENTER ONE OF THE FOLLOWING'
      WRITE(*,6)
      WRITE(*,*)'1:   TO CALCULATE RELATIVE SUSPENSION DISPLACEMENT'
      WRITE(*,*)'2:   TO CALCULATE VERTICAL SPRUNG MASS ACCELERATION'
      WRITE(*,*)'3:   TO CALCULATE MODELED DYNAMIC LOAD'

      READ(*,*)ANS

      WRITE(*,*)'... WAIT, PROCESSING CONTINUES'
C     Starting the do loop for reading the data from the file

      DO 17 I=1,5000
      READ(8,*,END=15)ATA(I)
 17   CONTINUE


 15   NPTS=I-1
      WRITE(11,6)
      WRITE(11,*)'TOTAL NUMBER OF DATA POINTS ARE:',NPTS
      WRITE(11,6)

      HINIT = 0.001
c     HINIT is Initial time step

      MXSTEP=50000
c     Max,. no. of steps allowed

      INORM = 2
      IMETH = 2
c     IMETH=1 --> Adams' Method, IMETH=2 --> Gears Method

      CALL SSET (NPARAM, 0.0, PARAM, 1)

      PARAM(1) = HINIT
```

```
      PARAM(4) = MXSTEP
      PARAM(10) = INORM
      PARAM(12) = IMETH
      IDO = 1

      IF(UCON.EQ.1)THEN
      P1=118.0
      P2=4.7
      P3=0.146
      P4=755.0
      P5=P1/P3
      P6=(P4/P3)+(P1/P3)
      P7=P2/P3
      P8=P4/P3
      P9=9.81/P1
C     P9 = Initial Condition y(1)

      P10=9.81*((1/P4)+(P3/P4))
c     P10 = Initial Condtion y(2)
      P20=10000.0
      P11=((P4*P20)/2.2046244)/1000.0
C     P11 = Value of Kt, i.e. tire spring constatnt in KN.
c     Here Sprung Mass used is 10000 lbs.
      ELSE

      P5=P1/P3
      P6=(P4/P3)+(P1/P3)
      P7=P2/P3
      P8=P4/P3
      P9=9.81/P1
C     P9 = Initial Condition y(1)

      P10=9.81*((1/P4)+(P3/P4))
c     P10 = Initial Condtion y(2)
      P11=((P4*P20)/2.2046244)/1000.0
C     P11 = Value of Kt, i.e. tire spring constatnt in KN.
      ENDIF


      IF(UCON.EQ.1)THEN
      WRITE(11,*)'USING DEFAULT CONSTANTS'
      ELSE
      WRITE(11,*)'USING USER SUPPLIED CONSTATNS'
      ENDIF
```

```
      WRITE(11,6)
      WRITE(11,*)'MECHANICAL CONSTATNS USED ARE:'
      WRITE(11,6)
      WRITE(11,41)P1,P4,P3,P2,P20
   41 FORMAT(1X,'Ks/Ms=',F7.3,/,1X,'Kt/Ms=',F5.1,/,1X,'Mu/Ms=',F6.4,
     +/,1X,'Cs/Ms=',F5.2,//,'Sprung Mass=',f8.1)


C     write(11,*)P1,P2,P5,P6,P7,P8,P11
c    Initials Conditions
c    ^^^^^^^^^^^^^^^^^^^^
      X = 0.0

C     Y(1) = 0.0831355
C     Y(2) = 0.0148904


      Y(1)=P9
      Y(2)=P10
      Y(3) = 0.0
      Y(4) = 0.0

      TOL = 1.0E-04

c    TOL is tolerence for error control

c     CALL UMACH (2,NOUT)
c     WRITE (NOUT,998)

      WRITE(11,6)
      IF(ANS.EQ.1)THEN
      WRITE(11,*)'CALCULATING RELATIVE DISPLACEMENT IN METERS'
      WRITE(11,6)
      WRITE (11,998)
      ELSEIF(ANS.EQ.2)THEN
      WRITE(11,*)'CALCULATING SPRUNG MASS ACCELERATION IN M/SEC^2'
      WRITE(11,6)
      WRITE(11,997)
      ELSEIF(ANS.EQ.3)THEN
      WRITE(11,*)'CAULATING MODELED DYNAMIC LOAD IN KN'
      WRITE(11,6)
      WRITE(11,996)
      .ENDIF
```

```
      DO 25 IEND=1,5000
      XEND=FLOAT(IEND)/100.0
      IDUM=IEND

C     Calling the subroutine from IMSL.
C     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^


      CALL IVPAG (IDO,NEQ,FCN,FCNJ,A,X,XEND,TOL,PARAM,Y)

C      SACC=-118.0*Y(1)+118.0*Y(2)-4.7*Y(3)+4.7*Y(4)
      SACC=-P1*Y(1)+P1*Y(2)-P2*Y(3)+P2*Y(4)
C     SACC= Sprung Mass Vertical Acceleration

C      DL=(Y(2)-((ATA(IDUM)/1000.0)*0.0254))*3424.6196
      DL=(Y(2)-((ATA(IDUM)/1000.0)*0.0254))*P11
C     DL= Modeled dynamic load

C      WRITE (NOUT,999)X,Y(1),y(2)


      IF (ANS.EQ.1)THEN
      WRITE (11,999)X,Y(1)-Y(2)
      ELSEIF(ANS.EQ.2)THEN
      WRITE (11,999)X,SACC
      ELSEIF(ANS.EQ.3)THEN
      WRITE(11,999)X,DL
      ENDIF

 25   CONTINUE

      IDO=3
      CALL IVPAG (IDO,NEQ,FCN,FCNJ,A,X,XEND,TOL,PARAM,Y)

998   FORMAT (4X,'T',6X,'Y(1)-Y(2)',/)

997   FORMAT (4X,'T',6X,'VERT. ACC.',/)

996   FORMAT (4X,'T',6X,'DYNAMIC LOAD',/)

999   FORMAT(1x,f5.2,F16.8,2x,f16.8)

      WRITE(*,6)
      WRITE(*,*)' OUTPUT FILE   ',FOUT
      WRITE(*,*)' HAS BEEN CREATED'
```

```
      END

C     Subroutine for placing the differential equations
C     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

      SUBROUTINE FCN (NEQ,X,Y,YPRIME)
      PARAMETER (NDIM=5000)
      INTEGER NEQ
      REAL T,Y(NEQ), YPRIME(NEQ)

      COMMON ATA(NDIM),IDUM
      COMMON P1,P2,P5,P6,P7,P8

      YPRIME(1) = Y(3)
      YPRIME(2) = Y(4)
C      YPRIME(3)=-118*Y(1)+118*Y(2)-4.7*Y(3)+4.7*Y(4)
C      YPRIME(4)=808.219*Y(1)-5979.466*Y(2)+32.192*Y(3)
C     1-32.192*Y(4)
C     2+5171.233*(((ATA(IDUM))/1000.0)*0.0254)

      YPRIME(3)=-P1*Y(1)+P1*Y(2)-P2*Y(3)+P2*Y(4)
      YPRIME(4)=P5*Y(1)-P6*Y(2)+P7*Y(3)-P7*Y(4)
     1+P8*(((ATA(IDUM))/1000.0)*0.0254)

      RETURN
      END

C     This subroutine is used to compute the Jacobian,
C     For this type of system of equations, it's not used.

      SUBROUTINE FCNJ (NEQ, T,Y,DYPDY)
      INTEGER NEQ
      REAL T,Y(NEQ),DYPDY(*)
      RETURN
C
      END


       This program calculates RMSVA and MAVA for profile roughness files

c      ***************************************************************************
c      program for calculating road roughness statistics RMSVA and MAVA  for roughness files
c      program rstat.for
```

```
c      ************************************************************************

       PARAMETER(ND=10000)
       DIMENSION ELE(ND),DATA(ND)
       CHARACTER FNAMEIN*20
       CHARACTER FNAMEOUT*20

       WRITE(*,*)'PLEASE WRITE THE INPUT FILENAME'
       READ(*,'(A)')FNAMEIN

       WRITE(*,*)'PLEASE WRITE THE OUTPUT FILENAME'
       READ(*,'(A)')FNAMEOUT

       OPEN(UNIT=11,FILE=FNAMEIN,FORM='FORMATTED',STATUS='OLD')
       OPEN(UNIT=8, FILE=FNAMEOUT,FORM='FORMATTED',STATUS='UNKNOWN')

c  starting of do loop for reading the data

       DO 19 I=1,10000
       READ(11,*,END=10)DATA(I)
       ELE(I)=(DATA(I)/1000)*.0254

 19    CONTINUE

c  ending of the do loop

 10    NPTS=I

c  npts = total no of data points in the given file

       WRITE(*,*)'NPTS=',NPTS

       WRITE(*,20)
 20    FORMAT(/////,T5,'WRITE',T25,'IF YOU WANT TO CALCULATE'
     1 ,/,T5,'1',T30,'RMSVA',/,T5,'2',T30,'MAVA')

       READ(*,*)IANS

       WRITE(*,*)'ENTER THE INTERVAL FOR WHICH YOU WANT TO'
     1 ,' CALCULATE RMSVA/MAVA'
       READ(*,*)N

       IF(IANS.EQ.1)THEN

       WRITE(8,21)N,FNAMEIN
```

```
      WRITE(*,21)N,FNAMEIN
 21   FORMAT(//,1X,'CALCULATING RMSVA(1/M) IN THE INTERVAL',I4
   + ,/,1X,'FOR THE INPUTFILE',1X,A20
   + ,/,1X,'THE DISTANCE IS IN METERS'/)

      ELSE

      WRITE(8,22)N,FNAMEIN
      WRITE(*,22)N,FNAMEIN
 22    FORMAT(//,1X,'CALCULATING MAVA(1/M) IN THE INTERVAL',1X,I4
   + ,/,1X,'FOR THE INPUTFILE',1X,A20
   + ,/,1X,'THE DISTANCE IS IN METERS'/)
      ENDIF

      M=NPTS/N
      M=M+1
      WRITE(*,*)'    INTERVAL    DISTANCE      VALUE'
      WRITE(8,*)'    INTERVAL    DISTANCE      VALUE'

c starting the first do loop

      DO 29 J=0,M-1

       SUM1=0.0
       SUM2=0.0
       MIN=N*J+1
       MAX=N*J+N

       IF(J.EQ.(M-1))MAX=NPTS-1
       DIST=MAX*(6.0*.0254)

c   starting of the second do loop

        DO 39 I=MIN,MAX

         X1=((ELE(I+1)+ELE(I-1)-2.0*ELE(I))/((6*0.0254)**2))**2
         X2=(ABS((ELE(I+1)+ELE(I-1)-2.0*ELE(I)))/((6*0.0254)**2))

         SUM1=SUM1+X1
         SUM2=SUM2+X2

 39      CONTINUE

c    ending of the second do loop
```

```
      RMSVA=(SUM1/(N-2))**0.5
      AMAVA=(ABS(SUM2)/(N-2))

      IF (IANS.EQ.1) WRITE(*,50)MIN,MAX,DIST,RMSVA
      IF (IANS.EQ.1) WRITE(8,50)MIN,MAX,DIST,RMSVA
      IF (IANS.EQ.2) WRITE(*,50)MIN,MAX,DIST,AMAVA
      IF (IANS.EQ.2) WRITE(8,50)MIN,MAX,DIST,AMAVA

 50    FORMAT(5X,I5,'-',I5,3X,F7.2,6X,E15.7)

 29   CONTINUE

c ending of the first do loop

      WRITE(*,*)'DO YOU WANT TO CONTINUE?'
      WRITE(*,*)'WRITE  1 IF YES'
      WRITE(*,*)'      0 IF NO'
      READ(*,*)IANS
      IF(IANS.EQ.1)GOTO 10

      STOP

      END
```

Program for calculating RMSVA and MAVA for dynamic loads

```
c     ********************************************************
c     This program calculates road roughness statistics RMSVA and MAVA
c     for dynamic load data files
c     program lstat.for

c     *********************************************************
      PARAMETER(ND=10000)
      DIMENSION ELE(ND)
      CHARACTER FNAMEIN*20
      CHARACTER FNAMEOUT*20
      WRITE(*,*)'PLEASE WRITE THE INPUT FILENAME'
      READ(*,'(A)')FNAMEIN
      WRITE(*;*)'PLEASE WRITE THE OUTPUT FILENAME'
    . READ(*,'(A)')FNAMEOUT
      OPEN(UNIT=11,FILE=FNAMEIN,FORM='FORMATTED',STATUS='OLD')
      OPEN(UNIT=8, FILE=FNAMEOUT,FORM='FORMATTED',STATUS='UNKNOWN')
```

```
c   starting of do loop for reading the data

      DO 19 I=1,10000
      READ(11,*,END=10)ELE(I)
 19   CONTINUE

c   ending of the do loop

 10   NPTS=I

c   npts = total no of data points in the given file

      WRITE(*,*)'NPTS=',NPTS

      WRITE(*,20)

 20   FORMAT(/////,T5,'WRITE',T25,'IF YOU WANT TO CALCULATE'
    1 ,/,T5,'1',T30,'RMSVA',/,T5,'2',T30,'MAVA')

      READ(*,*)IANS

      WRITE(*,*)'ENTER THE INTERVAL FOR WHICH YOU WANT TO'
    1 ,' CALCULATE RMSVA/MAVA'

      READ(*,*)N

      IF(IANS.EQ.1)THEN
      WRITE(8,21)N,FNAMEIN
      WRITE(*,21)N,FNAMEIN
 21   FORMAT(//,1X,'CALCULATING RMSVA(KN/M**2) IN THE INTERVAL',I4
    + ,/,1X,'FOR THE INPUTFILE',1X,A20
    + ,/,1X,'THE DISTANCE IS IN METERS'//)

      ELSE

      WRITE(8,22)N
      WRITE(*,22)N
 22   FORMAT(//,1X,'CALCULATING MAVA(KN/M**2) IN THE INTERVAL',I4
    + ,/,1X,'FOR THE INPUTFILE',1X,A20
    + ,/,1X,'THE DISTANCE IS IN METERS',//)
      ENDIF

      WRITE(*,24)
 24   FORMAT(//,1X,'ENTER THE VEHICLE SPEED IN KM/H')
```

```
      READ(*,*)D

      S=(D*5/18)*0.01

c converting vehicle speed into m/s and then dividing it by 100 to obtain
c the space interval in meters.

       M=NPTS/N
      M=M+1
      WRITE(*,*)'    INTERVAL    DISTANCE     VALUE'
      WRITE(8,*)'    INTERVAL    DISTANCE     VALUE'

c starting the first do loop

      DO 29 J=0,M-1
       SUM1=0.0
       SUM2=0.0
        MIN=N*J+1
       MAX=N*J+N
        IF(J.EQ.(M-1))MAX=NPTS-1
       DIST=MAX*S

c   starting of the second do loop

        DO 39 I=MIN,MAX
         X1=((ELE(I+1)+ELE(I-1)-2.0*ELE(I))/(S**2))**2
         X2=(ABS((ELE(I+1)+ELE(I-1)-2.0*ELE(I)))/(S**2))

         SUM1=SUM1+X1
         SUM2=SUM2+X2

 39      CONTINUE

c    ending of the second do loop

        RMSVA=(SUM1/(N-2))**0.5
        AMAVA=(ABS(SUM2)/(N-2))

        IF (IANS.EQ.1) WRITE(*,50)MIN,MAX,DIST,RMSVA
        IF (IANS.EQ.1) WRITE(8,50)MIN,MAX,DIST,RMSVA
        IF (IANS.EQ.2) WRITE(*,50)MIN,MAX,DIST,AMAVA
        IF (IANS.EQ.2) WRITE(8,50)MIN,MAX,DIST,AMAVA

 50     FORMAT(5X,I5,'-',I5,3X,F7.2,6X,E15.7)
```

```
 29     CONTINUE

c ending of the first do loop

        WRITE(*,*)'DO YOU WANT TO CONTINUE?'
        WRITE(*,*)'WRITE  1 IF YES'
        WRITE(*,*)'       0 IF NO'
        READ(*,*)IANS
        IF(IANS.EQ.1)GOTO 10

        STOP

        END
```

The quarter-truck model developed on UNIX system using software MATLAB (UNIX is case sensitive!)

```
global M
load /a/decserv1.coea.wsu.edu/users/ce/mgujarat/asc/dsit160.mat;
imax=length(aa);
t1=0;
t2=0.01;
x0=[.0831355 .0148904 0 0]';
count=0;
for i=1:imax
M=(aa(i)/1000)*0.0254;
i
[T,Y]=ode23('truck',t1,t2,x0);
t1=t2;
t2=t1+0.01;
x0=Y(length(T),:);
savY(count+1,:) = x0;
savT(count+1) = t2;
%dl(count+1)=(savY(1)-M)*3424.6196
%savY(count+1:count+length(T), :) = Y;
%savT(count+1:count+length(T)) = T;
count=count+1;
clear T Y;
hold on;
end;
%subplot 211
%plot(savT,savY(:,1));
%axis([0 5 -.001 .001])
```

```
%orient tall;
%subplot 212
%plot(savT,savY(:,2));
%axis([0 5 -.005 .005])
%orient landscape;
%orient tall;
%subplot 223
%plot(savT,savY(:,3));
%subplot 224
%plot(savT,savY(:,4));
dl=(savY(:,2)-M)*3424.6196;
save dlqt dl;
ac=-118*savY(:,1)+118*savY(:,2)-4.7*savY(:,3)+4.7*savY(:,4);
%save acqt560 ac;


function f=truck(t,x)
global M
f(1)=x(3);
f(2)=x(4);
f(3)=-118*x(1)+118*x(2)-4.7*x(3)+4.7*x(4);
f(4)=808.219*x(1)-5979.466*x(2)+32.192*x(3)-32.192*x(4)+5171.233*M;
```

A sample transfer function program develope on UNIX system using software MATLAB.

```
clear;
load /a/decserv1.coea.wsu.edu/users/ce/mgujarat/asc/dsit160.mat;
load /a/decserv1.coea.wsu.edu/users/ce/mgujarat/asc/dsit360.mat;
load /a/decserv1.coea.wsu.edu/users/ce/mgujarat/asc/dsit560.mat;
sit1=(aa/1000)*.0254;
sit3=(bb/1000)*.0254;
sit5=(cc/1000)*.0254;
load /a/decserv1.coea.wsu.edu/users/ce/mgujarat/rfile/rr30an.dat;
load /a/decserv1.coea.wsu.edu/users/ce/mgujarat/rfile/rr14an.dat;
load /a/decserv1.coea.wsu.edu/users/ce/mgujarat/rfile/rr17an.dat;
[txy1,f]=tfe(sit1,rr30an,256,100);
[txy3,f]=tfe(sit3,rr14an,256,100);
[txy5,f]=tfe(sit5,rr17an,256,100);
tp1=abs(txy1);
tp3=abs(txy3);
tp5=abs(txy5);
dd=[1 1 1 1 ]/4;
ee=1;
y1=filter(dd,ee,tp1);
```

```
plot (f,y1,'y-',f,y3,'r-.',f,y5,'m--')
axis([0 30 0 8000])
title('Dynamic Load / Profile, 60 kmph , Rubber');
xlabel('FREQUENCY (Hz)');
ylabel('TRANSFER FUNCTION (N/mm)');
orient portrait
gtext('__ site1, _. site3, -- site5');
```

Code for 'Truck Response to Roughness Index', TRRI, giving proposed statistic

```
c ************************************************************************
c * This Program should be linked with IMSL software                     *
c *                                                                      *
c * This program is TRRI, 'Truck Response to Roughness Index'.           *
c * It calculates the proposed pavement roughness statistic              *
c * based on the reference vertical sprung mass acceleration             *
c * transfer function obtained by quarter-vehicle simulation             *
c * developed.                                                           *
c *                                                                      *
c * It calculates the power spectral density of the profile              *
c * elevations from the IMSL subroutine SSWD. Then profile               *
c * power spectral density is multiplied by the square of the            *
c * transfer function to yield the spectral density of the              *
c * sprung mass acceleration, which in turn is integrated  over          *
c * the full range of frequencies of 0 to 50 Hz. Numerical               *
c * integration technique of Simpson's Rule is used to carry             *
c * out the integration. The pavement roughness statistics TRRI          *
c * is obtained as the square root of the integral calculated.           *
c *                                                                      *
c * It asks the user following input.                                    *
c * *   The input file containing the profile elevations.                *
c *     This file should be in ASCII or dos text format.                 *
c *     and it should contain profile elevations in 1000 th              *
c *     of an inches and measurement at speed of 60 kmph.                *
c * *   The option for printing the power spectral density               *
c *     vaues in the file                                                *
c * **********************************************************************


      PROGRAM TRRI

      INTEGER IPRINT,LDPM,LDSM,NF,NM,NOBS
C
```

```
      PARAMETER (IPRINT=0,NF=129,NM=1,NOBS=3000,
     1LDPM=NOBS,LDSM=NF,PI=3.141492654)
SD400070
      DIMENSION TF(129),PR(129)

      INTEGER I,IFSCAL,ISWVER,M(NM),NOUT,NPAD
      REAL F(NF),PM(LDPM,5),REAL,FLOAT,
     3SM(NF,5),SSUM,TINT,X(NOBS),XCNTR
      INTRINSIC REAL

      EXTERNAL SSUM,SSWD,UMACH

C     COMMON/WORKSP/RWKSP
C     REAL RWKSP(12000)
C     CALL IWKIN(12000)


      CHARACTER*20 FIN
      CHARACTER*20 FOUT
      CHARACTER*20 FPSD

      WRITE(*,*)'PLEASE WRITE THE INPUT FILENAME'
      READ(*,'(A)')FIN
      WRITE(*,*)'PLEASE WRITE THE OUTPUT FILENAME'
      READ(*,'(A)')FOUT
      WRITE(*,5)
    5 FORMAT(/////)
    6 FORMAT(//)
      WRITE(*,*)'DO YOU WANT TO WRITE THE POWER SPECTRAL DENSITY (PSD)'
      WRITE(*,*)'IN AN OUTPUT FILE'
      WRITE(*,*)' WRITE 1 IF YES'
      WRITE(*,*)'       2 IF NO'
      READ(*,*)APS
      WRITE(*,6)
      IF (APS.EQ.1)THEN
      WRITE(*,*)'PLEASE WRITE THE PSD FILENAME'
      READ(*,'(A)')FPSD
      OPEN(UNIT=11,FILE=FPSD)
      ENDIF
      WRITE(*,6)
      WRITE(*,*)'....WAIT, PROCESS CONTINUES'

      OPEN(UNIT=8,FILE=FIN)
      OPEN(UNIT=9,FILE=FOUT)
      OPEN(UNIT=10,FILE='TRANSFUN.DAT')
```

```
      DO 21 I=1,3000
       READ(8,*)X(I)
       X(I)=(X(I)/1000)*.0254
   21 CONTINUE

      DO 22 I=1,129
       READ(10,*)TF(I)
   22 CONTINUE

      XCNTR = SSUM(NOBS,X,1)/REAL(NOBS)
C      NPAD = NOBS-1
      NPAD = 0
      IFSCAL = 0

      DO 10 I=1,NF
      F(I) = PI*REAL(I)/REAL(NF)
   10 CONTINUE
      TINT=1
      M(1) = 10

      ISWVER = 1

      CALL SSWD (NOBS,X,IPRINT,XCNTR,NPAD,IFSCAL,NF,F,TINT,
     1ISWVER,NM,M,PM,LDPM,SM,LDSM)


      IF (APS.EQ.1)THEN
      WRITE(11,*)'POWER SPECTRAL DENSITY FOR SITE  ',FIN
      WRITE(*,7)
      WRITE(11,*)'   FREQUENCY    PSD '
      WRITE(*,7)
    7 FORMAT(//)
      DO 30 I=1,NF-1
      FR=I*.390625
      WRITE (11,996) FR,SM(I,3)
  996 FORMAT(1X,F9.4,2X,E12.6)
   30 CONTINUE
      ENDIF

c     Multiplying square of transfer function by PSD of profile
c     elevation

      DO 24 I=1,129
       PR(I)=(TF(I)*TF(I))*SM(I,3)
```

```
 24 CONTINUE


c    The following steps are for calculating the area under the
c    curve of sprung mass acceleration spectrum using Simpson's
c    one third rule.


      A=0.0
      H=0.3906
      B=50.0

c      A = lower limit
c      H= time step
c      B= upper limit

      XI0=PR(1)+PR(129)
      XI1=0.0
      XI2=0.0

      DO 25 I=2,128
       X=A+I*H
       IF(MOD(I,2).EQ.0)THEN
       XI2=XI2+PR(i)
      ELSE
        XI1=XI1+PR(i)
      ENDIF
 25 CONTINUE

      XI=H*(XI0+4*XI2+2*XI1)/3
      XI=SQRT(XI)
      WRITE(*,26)XI
      WRITE(9,*)'THE ACCUMULATED VERTICAL SPRUNG MASS ACCELERATION'
      WRITE(9,*)'FOR THE SITE ',FIN
      WRITE(9,26)XI
 26 FORMAT(/,1X,E8.2,2X,'M/SEC^2')


      STOP
      END
```