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"Roughness Index for Trucks"

**A ROUGHNESS MODEL DESCRIBING
HEAVY VEHICLE-PAVEMENT INTERACTION**

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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:

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

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

where, M_s and M_u are the sprung and unsprung 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

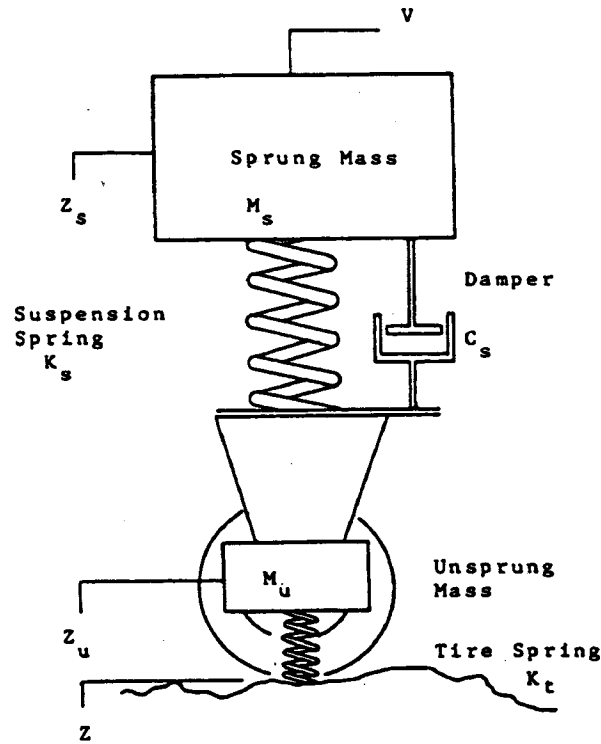


Figure 1: Quarter-Car Simulation, (After Gillespie et al, 1980)

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).

$$ARV = \frac{1}{T} \int_0^T |\dot{Z}_s - \dot{Z}_u| dt \quad (3)$$

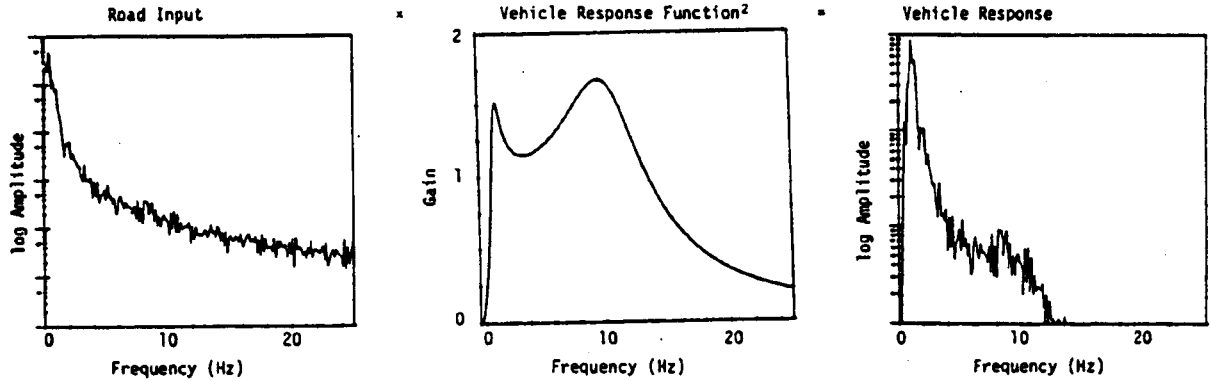


Figure 2: Contribution of Vehicle and Road Input to the Spectral Density of the Relative Axle-Body Displacement, (After Gillespie et al, 1980).

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:

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

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.

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

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:

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

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 / sec²), exhibiting a very good fit:

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

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*.

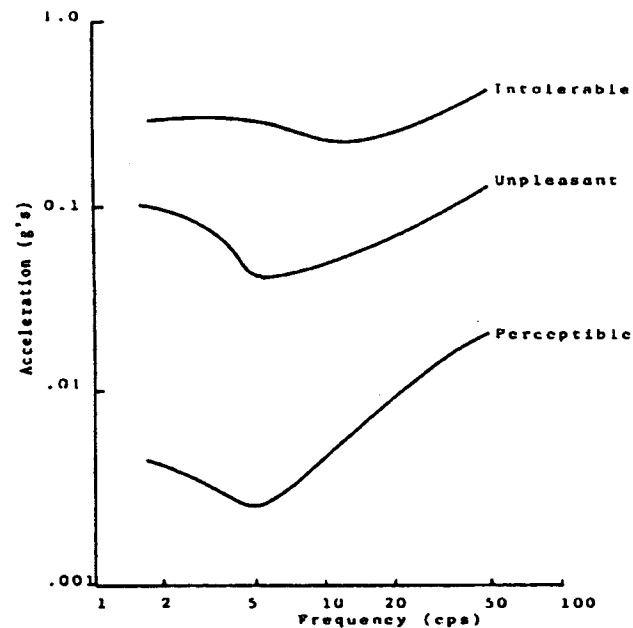


Figure 3: Subjective Tolerance Levels for Vertical Acceleration, (After Goldman, 1948)

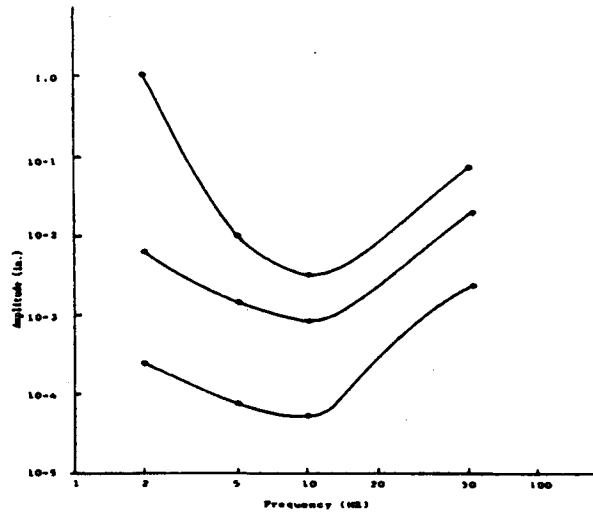


Figure 4: Amplitudes corresponding to Isocomfort Curves in Fig. 3, (After Hudson et al, 1985).

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).

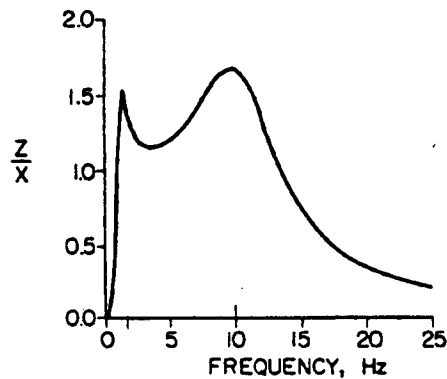


Figure 5: Transfer Function Sprung Mass minus Unsprung Mass Displacements versus Roughness Amplitude, (After Wambold et al, 1985).

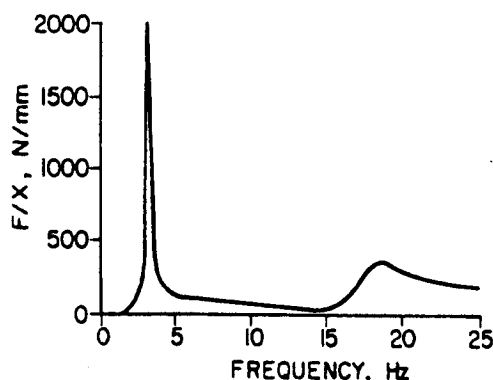


Figure 6: Transfer Function of Tire Load versus Roughness Amplitude for a Quarter-Truck, (After Wambold et al, 1985).

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.

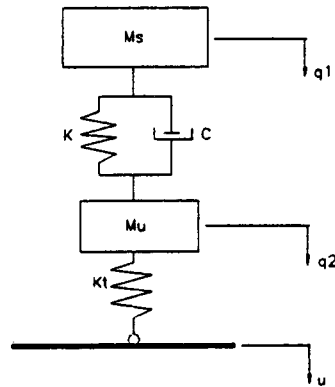


Figure 7: Quarter-Truck Model, (After Todd et al, 1989)

$$\dot{q}_1 = \dot{q}_3 \quad (8)$$

$$\dot{q}_2 = \dot{q}_4 \quad (9)$$

$$\dot{q}_3 = [(-\dot{q}_1 K + \dot{q}_2 K - \dot{q}_3 C + \dot{q}_4 C)]/M_s \quad (10)$$

$$\dot{q}_4 = [(\dot{q}_1 K - \dot{q}_2 (K_t + K) + \dot{q}_3 C - \dot{q}_4 C + u K_t)]/M_u \quad (11)$$

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 lbsec ² /in
M_u	Unsprung mass	2.976 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).

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

where,

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

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

where,

F_i = tire force at the i th 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.

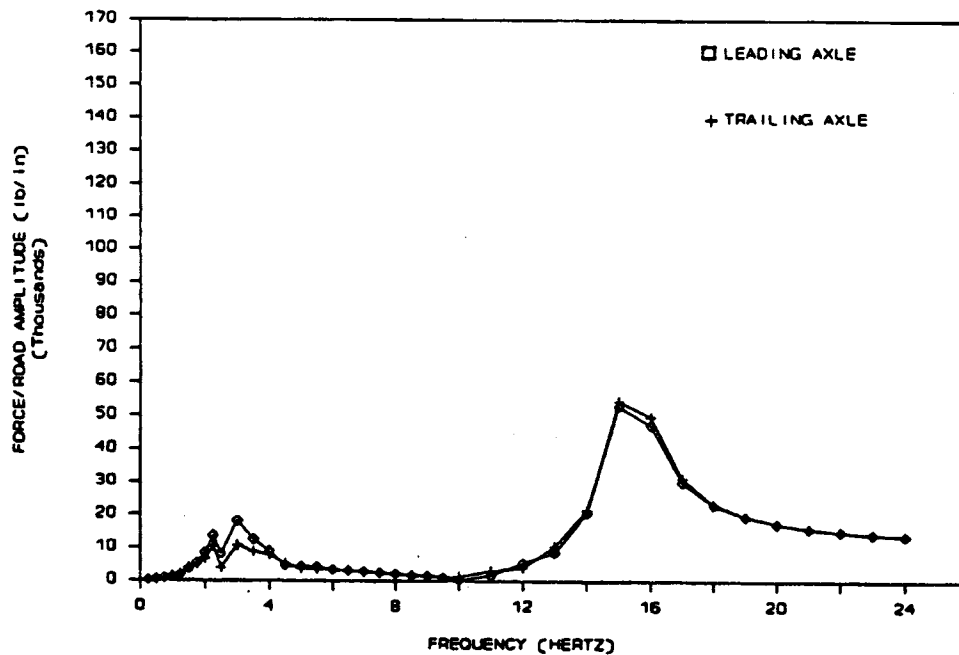


Figure 8: Transfer Function of Dynamic Tire Load versus Pavement Roughness Profile, (After Todd et al, 1989).

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.

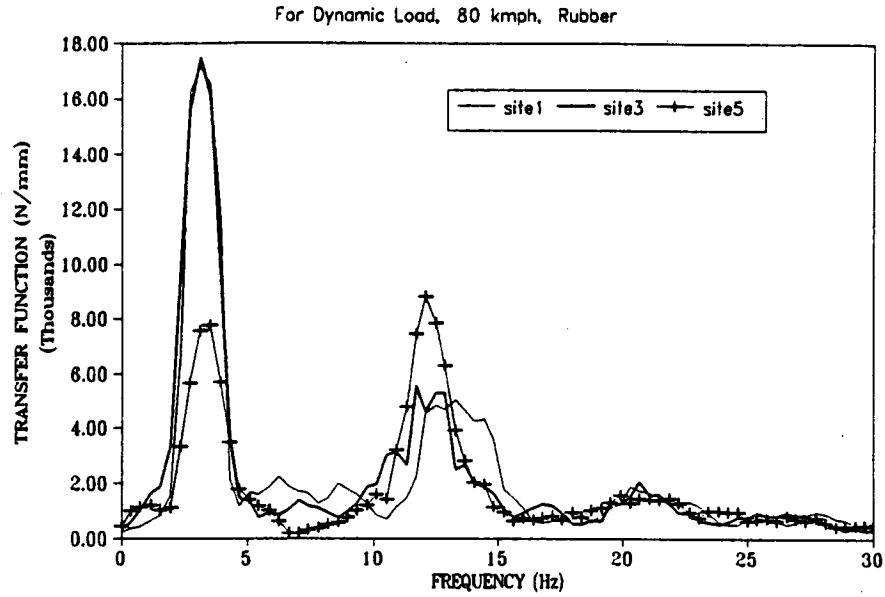


Figure 9: Transfer Function of Dynamic Load versus Profile Elevation Difference;
Rubber Suspension at 80 *km/h*.

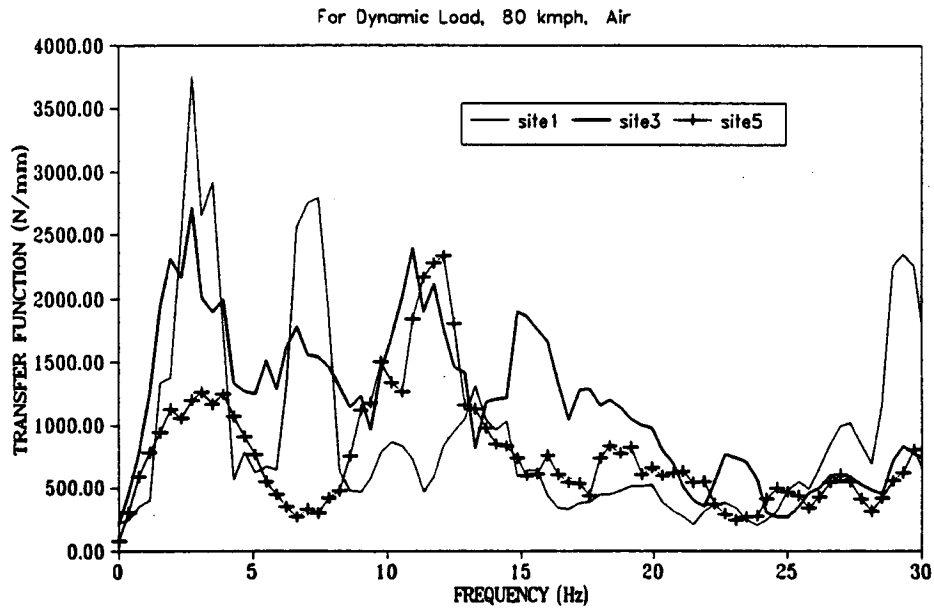


Figure 10: Transfer Function of Dynamic Load versus Profile Elevation Difference;
Air Suspension at 80 *km/h*.

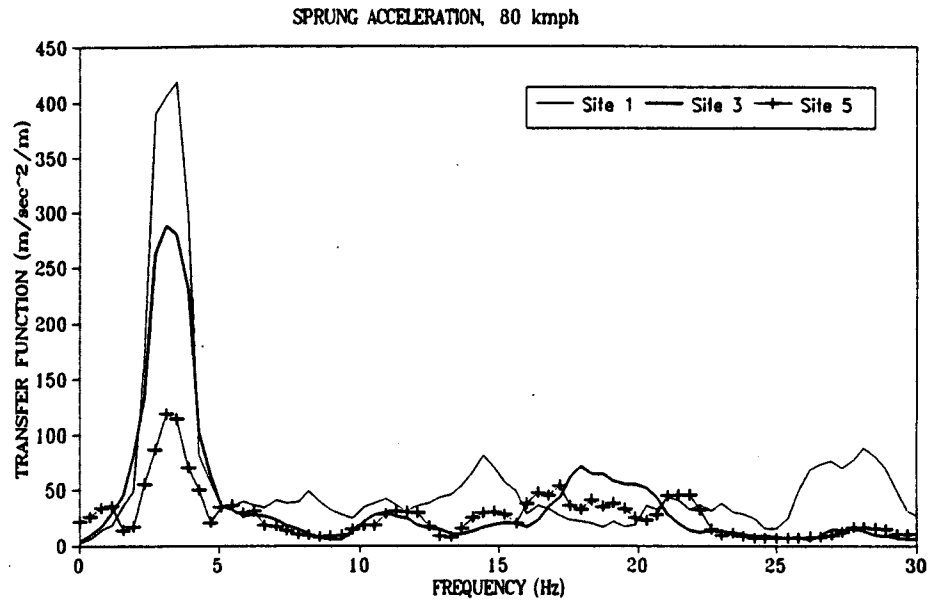


Figure 11: Transfer Function of Vertical Sprung Mass Acceleration versus Profile Elevation Difference at 80 km/h.

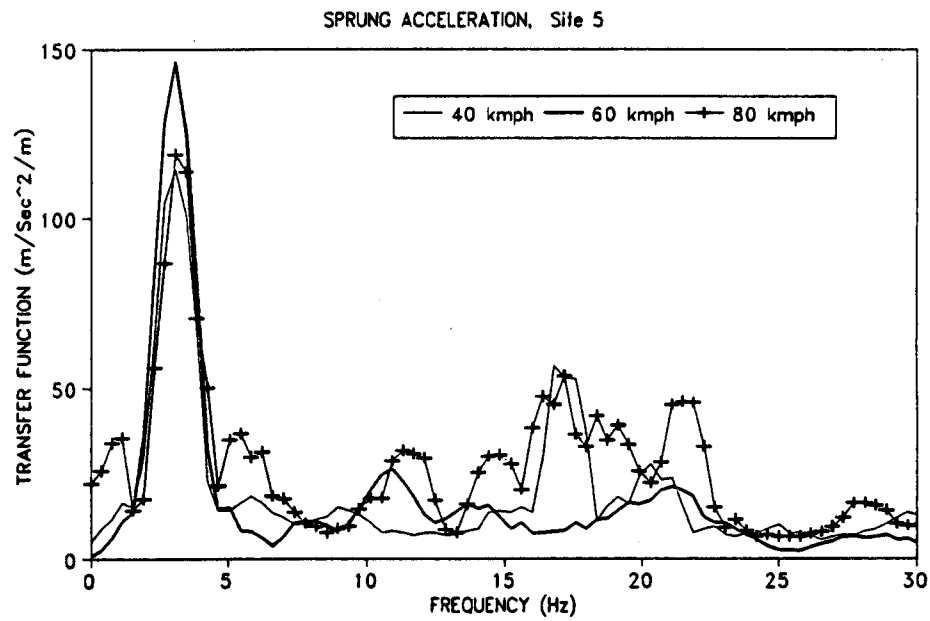


Figure 12: Transfer Function of Vertical Sprung Mass Acceleration versus Profile Elevation Difference for Site 5.

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.

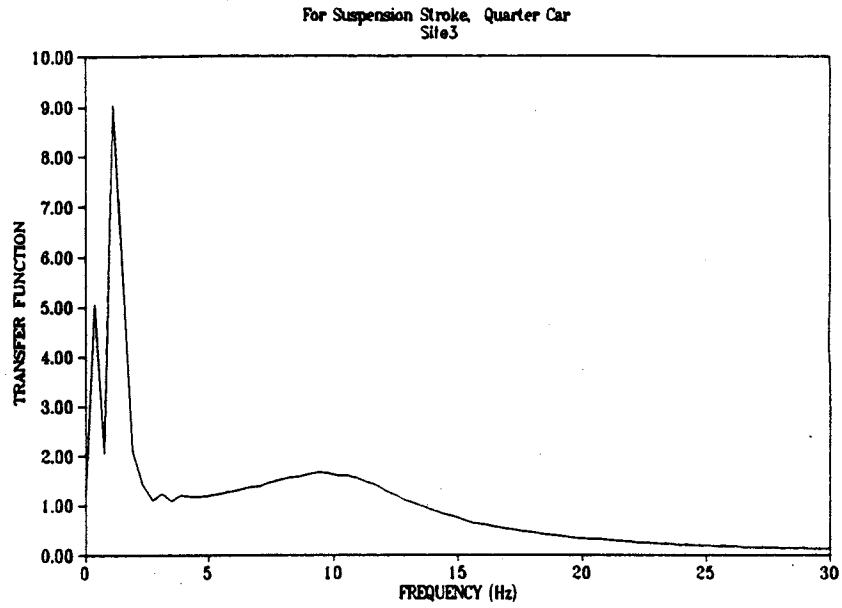


Figure 13: Transfer Function of the *ARS* versus the Profile Elevation Difference; Quarter-Car Model at 80 km/h, (Site 3).

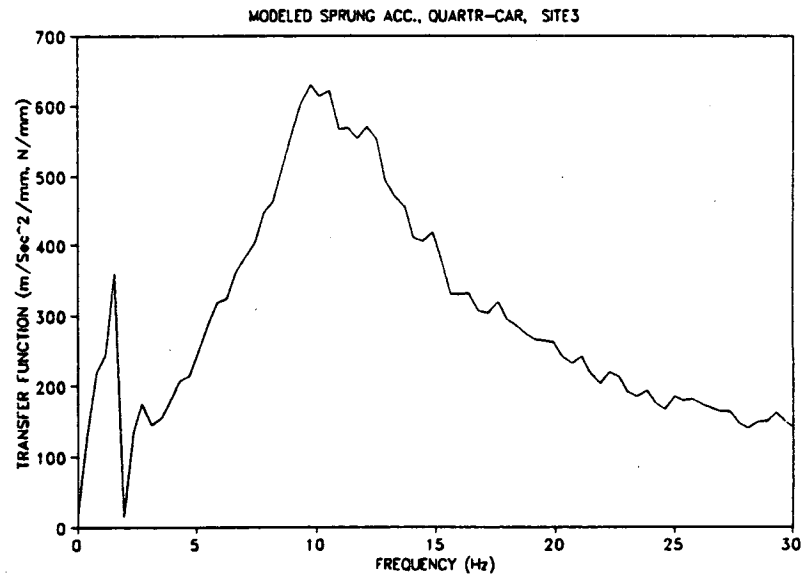


Figure 14: Transfer Function of Vertical Sprung Mass Acceleration versus Profile Elevation Difference; Quarter-Car Model at 80 km/h, (Site 3).

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/sec²). 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.

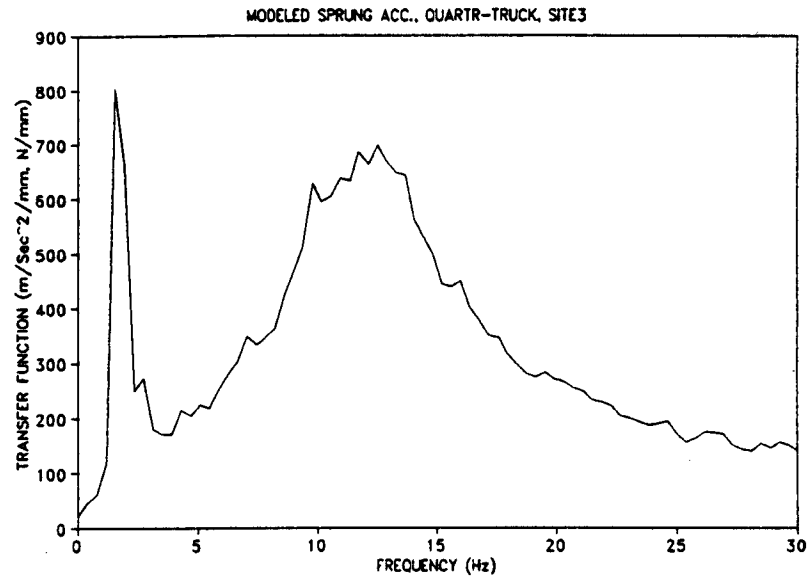


Figure 15: Transfer function of the Sprung Mass Acceleration versus Profile Elevation Differ.; Quarter-Truck Model at 80 km/h, (Site 3).

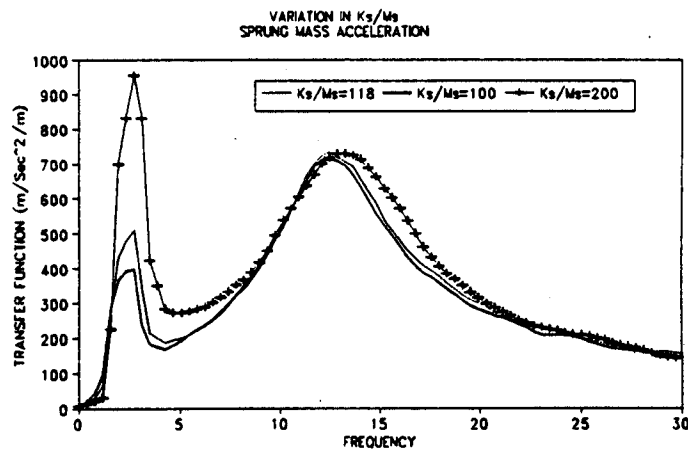


Figure 16: Effect of the Mechanical Constants of the Quarter-Vehicle on the Transfer Function of the Sprung Mass Acceleration versus Profile Elevation Differ., (Site 3).

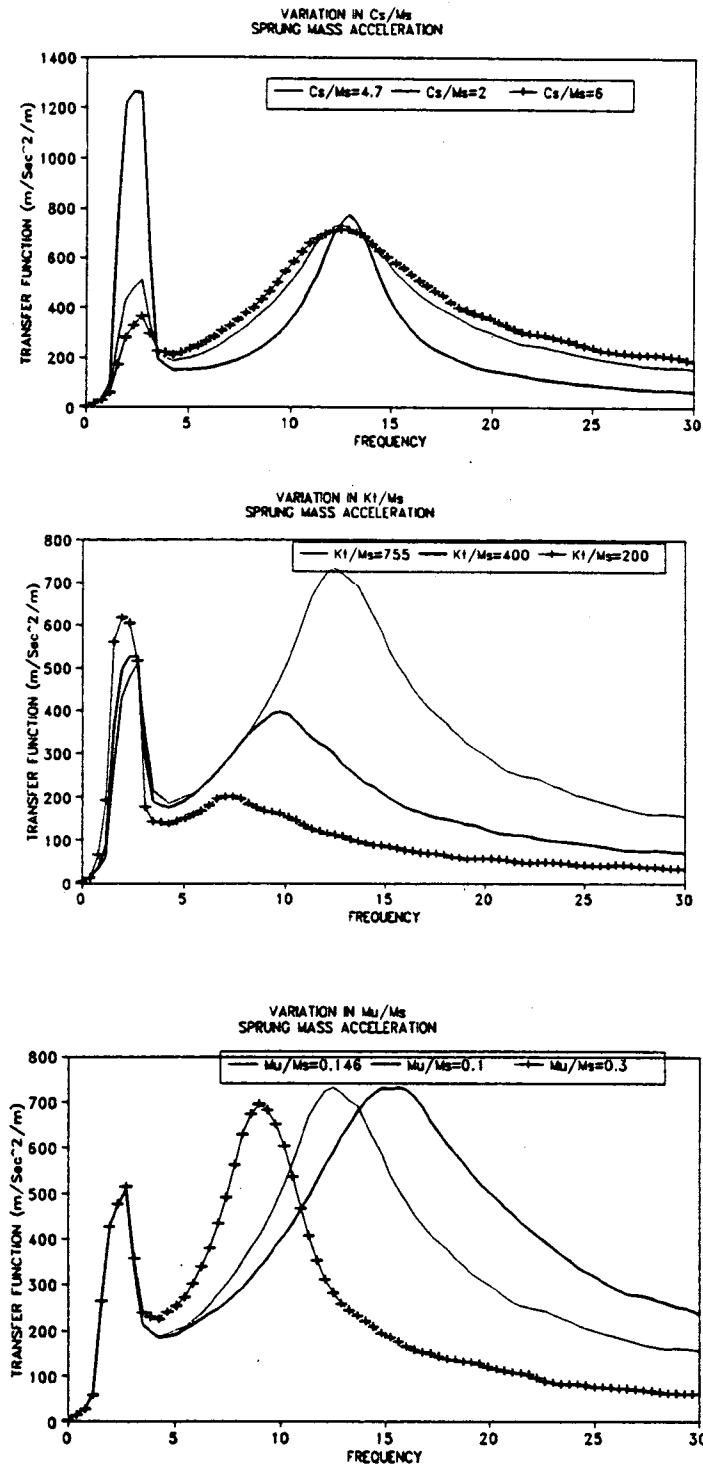


Figure 16, (Cont.): Effect of the Quarter-Vehicle Constants the Transfer Function of the Sprung Mass Acceleration versus Profile Elevation Differ., (Site 3).

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 purpose, 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 ($m / \text{sec}^2 / km$) 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. $m / \text{sec}^2 / km * 10^6$
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.

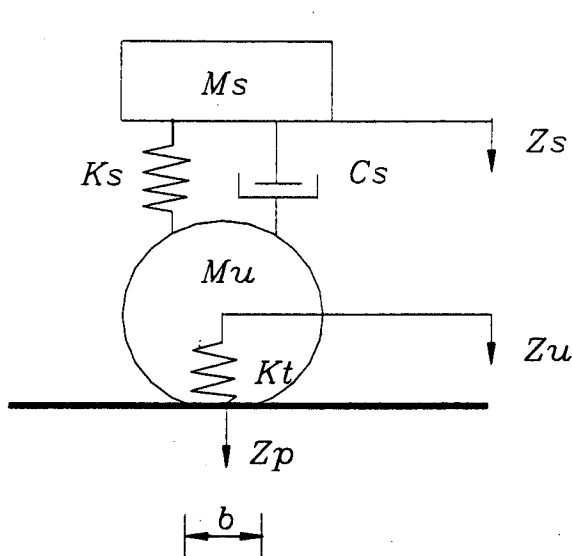


Figure A-1: Quarter-Vehicle Model

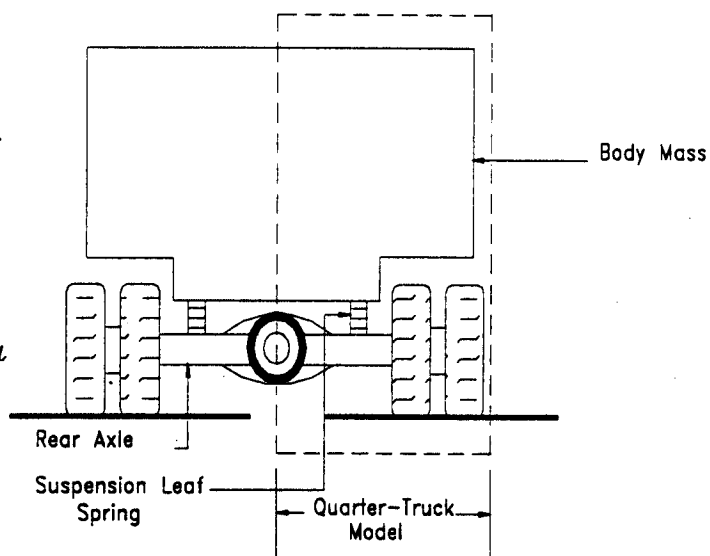


Figure A-2: Outline of Quarter-Vehicle Model

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

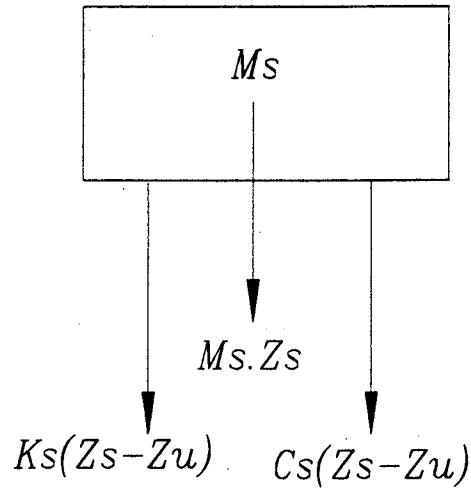


Figure A-3: Free body Diagram of Sprung Mass

Taking the equilibrium in Y direction of Cartesian coordinate axes,

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

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.

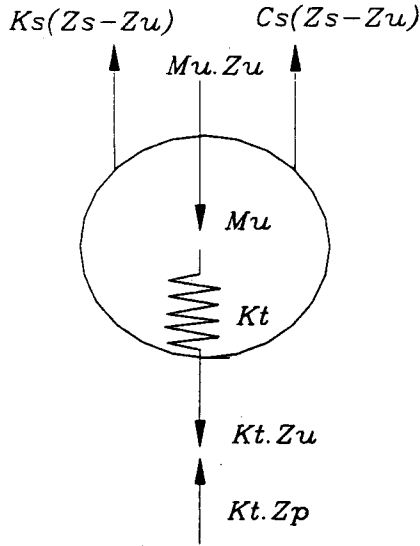


Figure A-4: Free Body Diagram of Unsprung Mass.

Taking equilibrium in Y direction, we get,

$$\sum F_y = 0$$

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

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

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:

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

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

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

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

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

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

$$\dot{Z}_1 = Z_3 \quad (A-7)$$

$$\dot{Z}_2 = Z_4 \quad (A-8)$$

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

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

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

$$K_s/M_s = 62.3 \quad \text{sec}^{-2}$$

$$K_t/M_s = 653 \quad \text{sec}^{-2}$$

$$M_u/M_s = 0.150$$

$$C_s/M_s = 6.0 \quad \text{sec}^{-1}$$

Putting these constants the quarter car model is described as:

$$\dot{Z}_1 = Z_3 \quad (A-11)$$

$$\dot{Z}_2 = Z_4 \quad (A-12)$$

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

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

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

$$Z_1(0) = M_s \cdot g / K_s = 0.1574638$$

$$Z_2(0) = (M_s + M_u) \cdot g / K_t = 0.00172764$$

$$Z_3(0) = 0.0$$

$$Z_4(0) = 0.0$$

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]

$$K_s/M_s = 118.0 \quad \text{sec}^{-2}$$

$$K_t/M_s = 755.0 \quad \text{sec}^{-2}$$

$$\text{Mu/Ms} = 0.146$$

$$\text{Cs/Ms} = 4.7 \quad \text{sec}^{-1}$$

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 *  $Z_s M_s + C_s(Z_s - Z_u) + K_s(Z_s - Z_u) = 0$  and
C * ..
C *  $Z_s M_s + M_u Z_u + K_t(Z_u - Z) = 0$ 
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 *  $K_s/M_s = 118 / \text{sec}^2$     $M_u/M_s = 0.146$ 
C *  $K_t/M_s = 755 / \text{sec}^2$     $C_s/M_s = 4.7 / \text{sec}$ 
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 NEO, NPARAM
PARAMETER (NEO=4, NPARAM=50, NDIM=5000)
C
COMMON ATA(NDIM), IDUM
C
COMMON P1, P2, P5, P6, P7, P8
C
INTEGER IDO, IMETH, INORM, NOUT, MXSTEP
REAL A(1,1), FCN, FCN1, HINT, PARAM(NPARAM), TOL, X, XEND, Y(NEO)
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 CONSTANS'
WRITE(*,*) '2: TO DEFINE YOUR OWN CONSTANS'
READ(*,*) UCON
IF(UCON.NE.1) THEN
WRITE(*,5)
WRITE(*,*) 'PLEASE ENTER Ks/Ms VALUE'
READ(*,*) P1

```

```

WRITE(*,*)PLEASE ENTER K/Ms VALUE
READ(*,*)P4
WRITE(*,*)PLEASE ENTER MU/Ms VALUE
READ(*,*)P3
WRITE(*,*)PLEASE ENTER C/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
HINIT is Initial time step
C
MXSTEP=50000
Max. no. of steps allowed
C
INORM = 2
IMETH = 2
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 Condition y(2)

```
P20=10000.0
```

```
P11=((P4*P20)/2.2046244)/1000.0
```

C P11 = Value of Kt, i.e. tire spring constant 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 Condition y(2)

```
P11=((P4*P20)/2.2046244)/1000.0
```

C P11 = Value of Kt, i.e. tire spring constant in KN.

```
ENDIF
```

```
IF(UCON.EQ.1)THEN
```

```
WRITE(11,*)'USING DEFAULT CONSTANTS'
```

```
ELSE
```

```
WRITE(11,*)'USING USER SUPPLIED CONSTANTS'
```

```
ENDIF
```

```

WRITE(11,6)
WRITE(11,*)'MECHANICAL CONSTANTS 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 tolerance 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,*)'CALCULATING 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

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 RMSVAMAVA'
  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,14
+ ,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,14
+ ,1X,FOR THE INPUTFILE,1X,A20
+ ,1X,THE DISTANCE IS IN METERS')
ENDIF
M=NPTS/N
M=M+1
WRITE(*,*)
WRITE(8,*)
INTERVAL  DISTANCE  VALUE
INTERVAL  DISTANCE  VALUE
c starting the first do loop
DO 29 J=0,M-1
SUM1=0.0
SUM2=0.0
MIN=N*f+1
MAX=N*f+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

```

```
OPEN(UNIT=11,FILE=FILENAME,FORM=FORMATTED,STATUS=OLD)
OPEN(UNIT=8,FILE=FILENAMEOUT,FORM=FORMATTED,STATUS=UNKNOWN)
```

```

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

```

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

Program for calculating RMSVA and MAVA for dynamic loads

END

STOP

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

ending of the first loop

29 CONTINUE

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

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

$$RMSEA = (\text{SUM1}/(N-2))^{*0.5}$$

c starting of do loop for reading the data

```
DO 19 I=1,10000  
  READ(11,*,END=10)ELE(I)  
  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,14  
  + ,/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,14  
  + ,/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,*)

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)-2.0*ELE(I))/(S**2))**2

X2=(ABS((ELE(I+1)+ELE(I)-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 develop 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);

```


PARAMETER (IPRINT=0,NF=129,NM=1,NOBS=3000,
 ILDPM=NOBS,LDSTM=NF,PI=3.141492654)
 SD400070
 DIMENSION TF(129),PR(129)

INTEGER I,JFSCAL,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
 C
 C
 COMMON/WORKSP/RWKSP
 REAL RWKSP(12000)
 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)
  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,NP,
  ISWVER,NM,M,PM,LDPM,SM,LDSM)
IF (APS.EQ.1)THEN
  WRITE(11,*)POWER SPECTRAL DENSITY
  WRITE(*,7)
  WRITE(11,*) FREQUENCY PSD
  WRITE(*,7)
7 FORMAT(//)
DO 30 I=1,NF-1
  FR=I*.390625
  WRITE (11,996) FR,SM(1,3)
996 FORMAT(1X,F9.4,2X,E12.6)
30 CONTINUE
  ENDIF
C Multiplying square of transfer function by PSD
C elevation
DO 24 I=1,129
  PR(I)=(TF(I)*TF(I))*SM(1,3)
PR(I)=(TF(I)*TF(I))*SM(1,3)

```

c	Multiplied square of transfer function by PSD of profile	c	elevation
---	--	---	-----------

c elevation

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