

Analyses of Moving Dynamic Loads on Highway Pavements: Part I — Vehicle Response

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ABSTRACT

This paper investigates the influence of heavy vehicle dynamics on flexible pavement response. In order to predict the forces at the road-tire interface full non-linear models were used to describe the dynamic behaviour of articulated vehicles traversing random flexible pavements. Both leaf-spring and air-bag suspensions are modeled.

A description is given of the mathematical representation of the dynamic vehicle-pavement interaction. Close examination shows that in order to characterize the effects of dynamic vehicle loads on pavement damage, it is necessary to know the frequency content of the load as well as the mean and variance. A modified Road Stress Factor is suggested for predicting the effects of varying suspension parameters on road cracking and rutting.

The final part of the study discusses the effects of varying various vehicle parameters on road damage calculated using VESYS (see part II) and using the modified Road Stress Factor. The parameters examined are suspension type, friction parameters, shock absorber damping, tire pressure, axle load sharing coefficients and suspension spring constants. The results of the parametric study show that a significant decrease in road damage can be achieved through careful suspension design.

INTRODUCTION

Due to the extensive highway network in the United States, the cost of maintaining the American highways has been outpacing available funding. In 1977, an estimated 14 billion dollars was required to maintain the highway system (1). While there are many factors that contribute to the degradation of the highways, this paper considers

only the effects of dynamic vehicle loads on pavement response. Recent studies (2,3) have suggested that dynamic vehicle loads may have significant impact on pavement performance, and the question that arises is if dynamic loads are important then should suspensions with small associated dynamic loads be allowed to carry heavier loads. For the purposes of pavement damage calculation, the tire force has been characterized by the mean and the coefficient of variation of the force. However, in order to quantify the dynamic effects fully it is necessary to look in more detail at how the pavement responds to a dynamic moving load. A modified Road Stress Factor is developed for the rutting and cracking pavement modes. This is suggested as a first cut design tool.

Various studies in the past have addressed the effect of dynamic vehicle loads on pavements, but to the author's knowledge, none have used an accurate measure of damage. Gorge (2) and Sweatman (3) use the Road Stress Factor, Φ

$$\begin{aligned}\Phi &= \left(\frac{1}{K}\right) E [F^4] \\ &= \left(\frac{1}{K}\right) E [F]^4 (1 + 6.DLC^2 + 3.DLC^4)\end{aligned}$$

where, K is the Axle Equivalence Factor, F is the Tire Force, and the DLC is the Dynamic Load Coefficient (the coefficient of variation of the tire force).

The DLC provides some insight into how road damage may be effected as various suspension characteristics are changed but it does not give the full picture. The above equation breaks down when parameters which affect the stress state in the road vary for example, tire pressure, and tandem axle spacing. The DLC also ignores the effects of the frequency distribution of the load, and coupling between tandem suspensions.

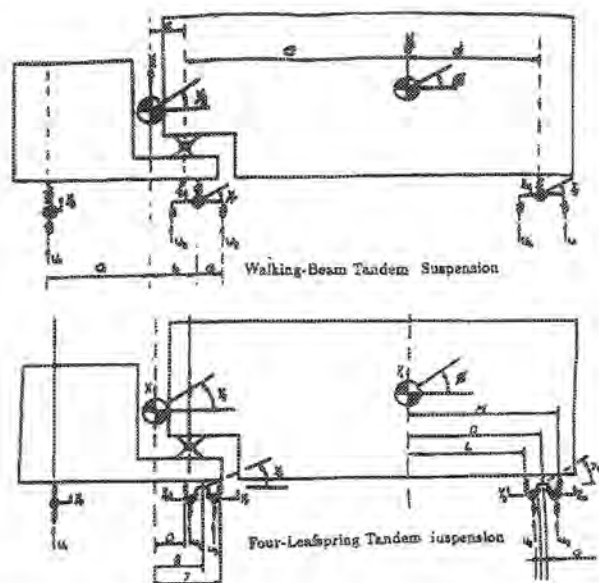
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The final part of the paper deals with parametric studies in which various suspension designs are assessed. Pavement damage is calculated using VESYS, as explained in the second part of the paper.

VEHICLE MODELLING

The purpose of this paper is to predict the effects of dynamic vehicle loads on flexible pavement degradation. The random response of vehicles to broad-band road inputs may be treated in the time domain or in the frequency domain using equivalent linearization techniques. The latter method is advantageous in that once the equations of motion have been linearized, alternative vehicle designs may be evaluated very efficiently. However, in this project an accurate prediction of the pavement primary response is required, thus making it necessary to know the tire force at each point in the pavement. It is also desirable to have models which deal with the system non-linearities in full. For the above reasons a time domain approach was adopted.

The models used are shown in Figure 1. The sprung masses associated with the tractor and trailer have bounce and pitch degrees of freedom, and the unsprung masses (suspensions) have a bounce degree of freedom and, in the case of the tandem suspension, a pitch degree of freedom. The



Schematic of vehicle models used in dynamic pavement load prediction

FIGURE 1

dynamics associated with sprung-mass roll are omitted.

SUSPENSION MODELS

There are many different suspension types currently being used on heavy commercial vehicles. The majority of the suspensions use the leaf spring as the compliant element. The second most common type is the air-bag suspension. Other types of suspension used include torsion bars and rubber elements such as the torsionless suspension (3).

Leaf-Spring Suspension

The three most common leaf-spring suspension geometries are shown in Figure 3. They are:

- the single axle suspension,
- the walking beam tandem axle suspension,
- the four-leaf tandem axle suspension

The basic suspension element, the leaf-spring, is made up of a number of steel beams which are allowed to slide over each other. As the leaves deflect, some energy is stored in the bending of the beams and the remainder is dissipated through inter-leaf and leaf-bracket friction. A typical force-deflection curve is shown in Figure 4. The leaf-spring characteristic is difficult to represent mathematically. The model used in this study is a modified version of the model developed by Fancher (4). The equation used is

$$F_t = F_{ENV_t} + (F_{ENV_{t-1}})e^{-|\delta_t - \delta_{t-1}| / \beta} \quad (1)$$

where

F_t is the suspension force at the current simulation time step

F_{t-1} is the suspension force at the last simulation time step

δ_t is the suspension deflection at the current simulation time step

δ_{t-1} is the suspension deflection at the last simulation time step

F_{ENV_t} is the force corresponding to the upper boundary when δ_t is increasing (or the force corresponding to the lower boundary when deflection is decreasing) at, and

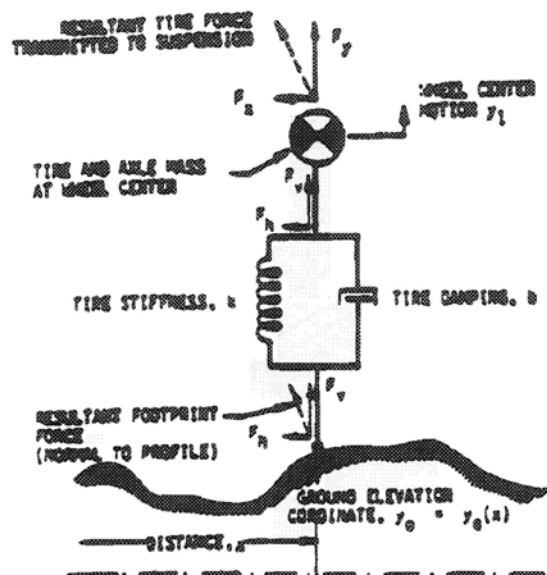
sure in the air spring in response to vehicle loading. In order to achieve this result without using excessive amounts of air, a time delay is incorporated in the design, which prevents the valve from functioning during a momentary change of axle to frame spacing which may occur while the vehicle traverses rough pavements. The delay is longer than one second, which is slower than the slowest vehicle vibration mode. Thus in a dynamic analysis the air in the air-bags may be treated as a closed system. In a dynamic analysis the air is continually being compressed and expanded at rates corresponding to the natural frequencies of the vehicle. The air in the bag does not have time to exchange heat with the surroundings because the heat transfer process has a relatively long time constant, so the gas compression/expansion process may be assumed to be adiabatic.

TIRE MODEL

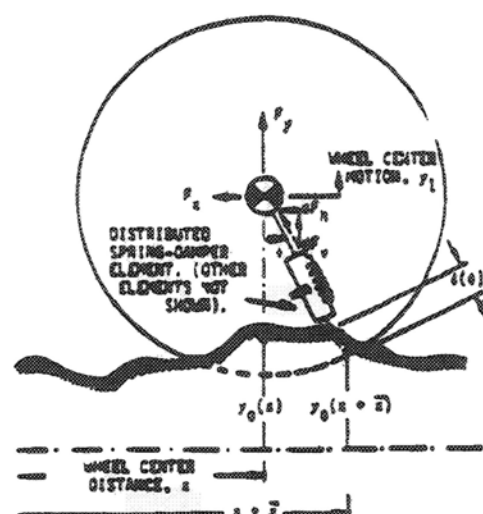
The tire model is critical to any investigation into the dynamic interaction between the vehicle and road. The tire acts as the primary suspension between the road and the vehicle, and the manner in which the tires transmit road disturbances dictates the vehicle's dynamic behaviour. Various models have been developed to account for this behaviour as illustrated in Figure 5. Adaptive-footprint tire models based on those developed in (7), were necessary in modelling vehicle response

to road inputs with sharp discontinuities (i.e. concrete faults and rumble strip). For the flexible pavements (broad-band input) examined in this study, however, the simple point contact model was found to be adequate.

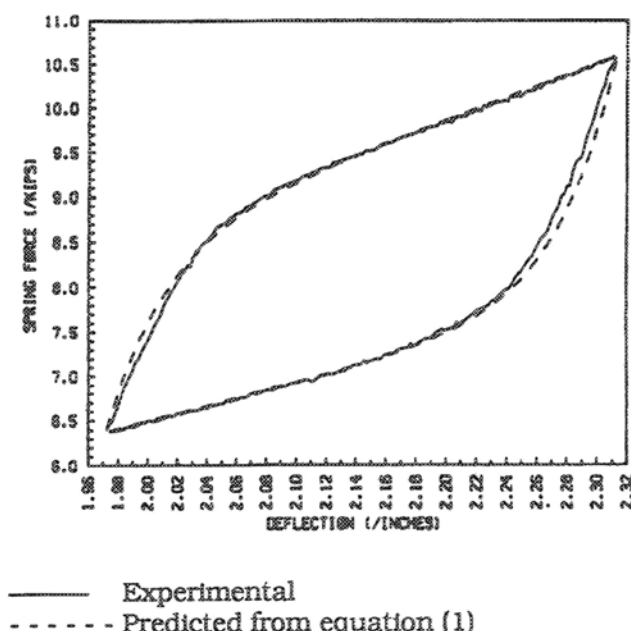
The manner in which the dynamic pavement loads are distributed at the road surface is also determined by the tire. In this study, the tire force is assumed to be uniformly distributed over a circular contact patch. The average contact area is



a) Point contact model



b) Adaptive footprint model



Typical static leaf-spring characteristics

FIGURE 4

Tire models (7)

FIGURE 5

found from the static characteristic. Figures 6a and 6b shows how the contact area and average contact pressure vary as a function of tire inflation pressure for various tire loads, for a Goodyear tire (12.75 R 22.5 Unisteel II with Rim 8.25).

VEHICLE EXCITATION

As a vehicle traverses a road, it will be excited by the road irregularities. In the case of flexible asphalt pavements, these irregularities will include pot-holes, due to localized pavement failure as well as random deviations in the road profile, due to imperfect construction and maintenance. Rigid pavements have their own characteristics which will affect vehicle response, such as periodic faults at slab connections. As this paper concentrates on the prediction of damage of flexible pavements, only excitation characteristic of these pavements is considered.

It has been shown (8), that a flexible road displacement profile may be considered as a realization of a stationary gaussian random process. The profile is, thus, fully described by its autocorrelation function, or the corresponding spectral density. The road PSD is flat for road frequencies below 0.01 cycles/ft, (Ω_0), above which it rolls off at the rate of -40dB/decade.

In this analysis the spectral density is represented by the mathematical expression:

$$S_y(\Omega) = \begin{cases} \frac{A}{(\Omega + \Omega_0)^2}, & \text{if } 0 \leq \Omega \leq \Omega_c; \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

where, A is the Road Roughness parameter; Ω_0 is the Road Break-frequency; and, Ω_c is the Cut-Off frequency above which there is negligible road input.

In this paper the road roughness is described by the variance of its spatial slope, or slope variance (SV). The slope variance may be related to the road roughness parameter as follows. The spectral density of the road slope, $S_s(\Omega)$, is given by

$$\begin{aligned} S_s(\Omega) &= S_y(\Omega) \cdot \Omega^2 \\ &= \frac{A \Omega^2}{(\Omega + \Omega_0)^2} \end{aligned} \quad (3)$$

The slope variance is given by

$$SV = \int_0^{\infty} S_s(\Omega) d\Omega. \quad (4)$$

If Ω_0 is small compared to Ω_c then

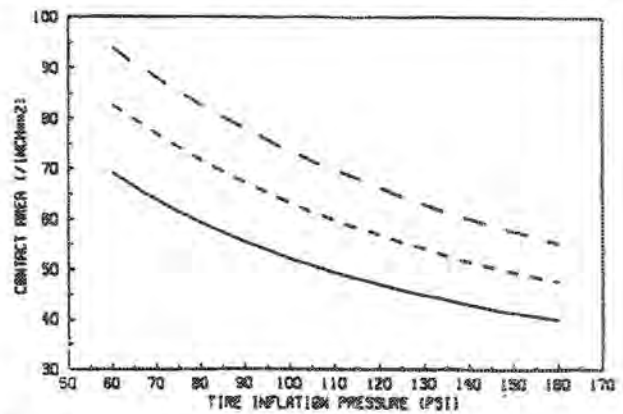
$$S_s(\Omega) \approx A,$$

and

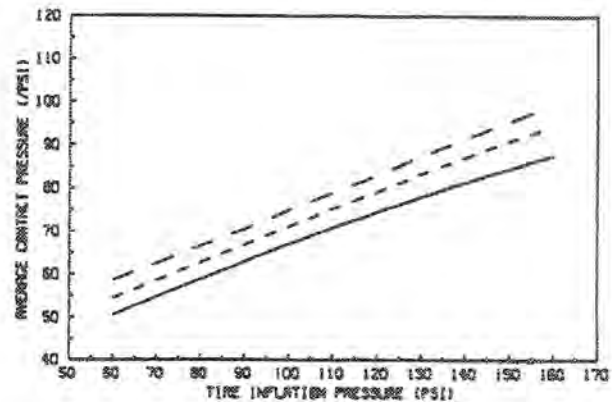
$$SV \approx A \Omega_c. \quad (5)$$

Time Domain Representation

In order to obtain a time domain representation of the road inputs for digital simulation purposes, Gaussian white noise was passed through a linear shaping filter. When statistically independent white noise samples are filtered, the shape of the



a) Contact area vs tire inflation pressure



b) Average contact pressure vs tire inflation pressure

— 3.5 kips/tire
 --- 4.5 kips/tire
 - - - 5.5 kips/tire

FIGURE 6

resulting power spectrum, is related to input spectrum, $S_o(\Omega)$, is related to the road roughness spectrum, $S_i(\Omega) = \text{constant}$, by the transfer function of the filter, $H(j\Omega)$, according to the equation

$$S_o(\Omega) = S_i |H(j\Omega)|^2 \quad (6)$$

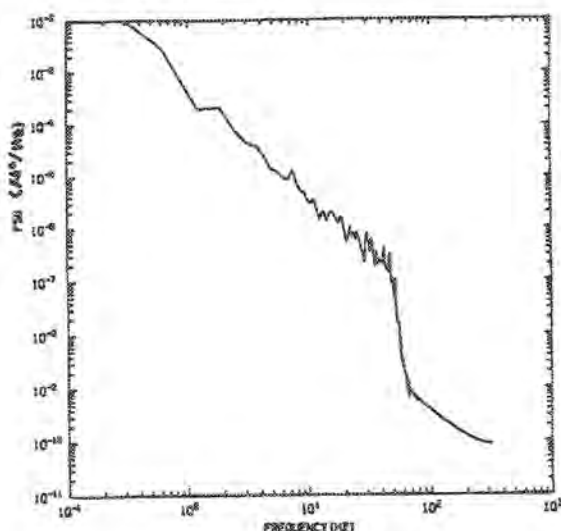
From equation (2), it can be seen that the transfer function of the desired filter is,

$$H(s) = H_r(s) H_b(s) \quad (7)$$

where

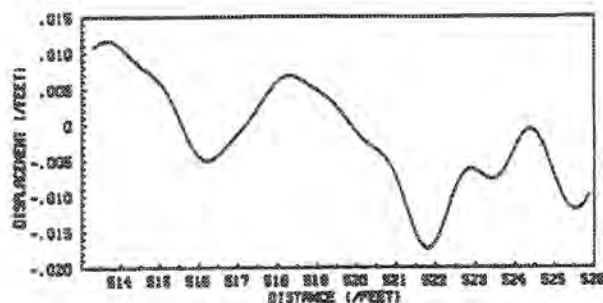
$$H_r(s) = \frac{1}{(s + \Omega_o)}$$

$$H_b(s) = \frac{1}{(s + \Omega_c)^n}$$



Computer-generated random road temporal power spectral density at 55 mph

FIGURE 7



The input Gaussian random numbers were generated using an IMSL subroutine. The number sequence generated had a PSD close to white noise. Figure 7 shows the power spectral density of the generated road profile. Figure 8 shows some typical road sections. Roads for various slope variances were obtained by scaling the base road generated by the square root of the required slope variance.

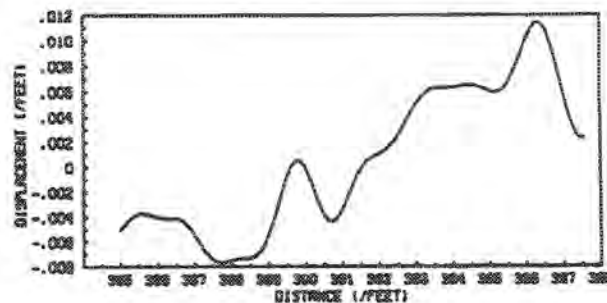
LOAD-PAVEMENT INTERACTION CHARACTERIZATION

INFLUENCE FUNCTIONS

The primary response of any point in the pavement (y, z) due to a unit step load at ($x, 0$) is generally a function of time, t , pavement geometry, G , and pavement materials properties, $M(E)$, given by $U(t, G, M(E))$. For vehicle speeds of interest, the dynamic effects in the pavement due to viscous and inertial terms are negligible (9), allowing the pavement response due to the movement of the vehicle over the road to be modelled as a quasi-static phenomenon. The response at y due to a unit load at x is thus characterized by the static (or elastic) response, $I(y - x)$. The function $I(y - x)$ is called the *Influence Function*. As a load traverses the pavement the response at y , $R(y)$, due to a load at x , $F(x)$ is given by

$$R(y) = I(y - x) F(x). \quad (8)$$

The primary response may be a stress, a strain, strain-energy or deflection. The influence functions for various primary responses were obtained using a modified version of VESYS IIIA (9), a pavement program which models flexible pavements as layered visco-elastic continuum. It was found that the normalized influence functions, could be regressed well (9) using the equation



Sample sections from computer-generated random road

FIGURE 8

$$\rho(x) = \cos^2\left(\frac{\pi}{2} \cdot \frac{ax^b}{1+ax^b}\right) \quad (9)$$

where a and b are regression constants.

Various normalized functions are plotted in Figure 9. They are symmetric with the maximum response occurring directly under the applied load. It is interesting to note that the influence function corresponding to longitudinal tensile strain is generally narrower than that corresponding to layer compressive strain or layer deflection. The influence function for a particular response parameter depends on the pavement materials properties, pavement layer thicknesses, as well as the area of contact between the tire and the road, and the associated contact-pressure distribution.

SINGLE AXLES

Constant Moving Load

Consider a constant load moving over a pavement. The force profile given as a function of distance down the pavement, x , is

$$F(x) = F_0$$

Consider a point y in the pavement. The load at y is zero for all time, except for when the load is directly overhead at time $t = t_y$. If the load is constant the normalized response at y as a function of time will have a shape similar to the in-

fluence function, where the horizontal axis has been transformed from the spatial domain, x , to the temporal domain, t , using, where v is the vehicle velocity.

Thus,

$$R(y, x) = \rho(y - x) F_0 \quad (10)$$

Assuming $x = vt$, then

$$R(y, vt) = \rho(y - vt) F_0$$

The point y has seen a cycle of distress of magnitude $R_p(y)$, where $R_p(y)$ is the value of the peak response at the point in question. This cycle contributes to the total pavement degradation at that y according to Miner's Law. We are interested in the average damage to the pavement. The ultimate response model essentially uses the statistics of the peak response to calculate road damage (9).

In this case, the peak response, R_p , occurs when the load is directly over the point of interest; thus the peak response at any point in the pavement is simply proportional to the value of the load at that point. For the rutting damage mode, the damage, Φ_R , is assumed to be related to the fourth power of the peak primary response (9), where the relevant primary response is the deflection (or compressive strain) at the top of the subgrade.

Thus

$$\Phi_R \propto E[R_p^4] \propto E[F^4] = F_0^4 \quad (11)$$

where $E[\]$ denotes the expectation operation taken over the whole pavement, y .

For the case of cracking in the surface layers, Φ_C the damage is related to the fifth power of the peak primary response (9), where the relevant primary response is now the longitudinal tensile strain at the bottom of the surface layer.

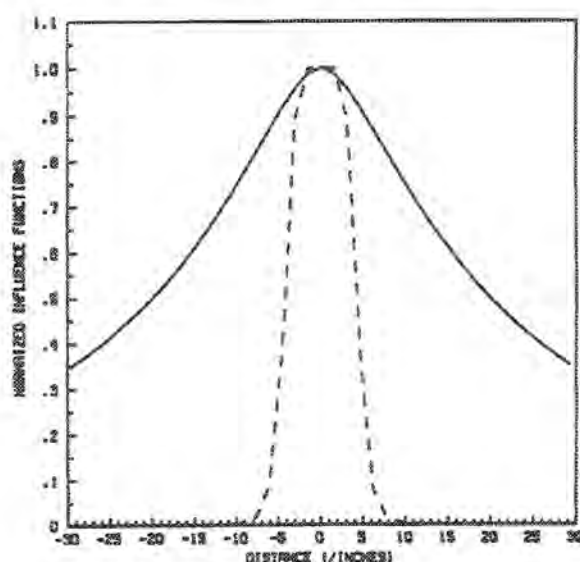
Thus

$$\Phi_C \propto E[R_p^5] \propto E[F^5] = F_0^5 \quad (12)$$

DYNAMIC MOVING LOAD

Consider a general dynamic load given by $F(x)$. As before the general response at y is given by

$$R(y, x) = \rho(y - x) F(x)$$



— Subgrade compressive strain
 - - - Surface layer longitudinal tensile strain

Typical normalized influence functions

FIGURE 9

or writing $x = vt$

$$R(y, vt) = \rho(y - vt) F(vt)$$

Unlike the constant load case the response is not symmetric and the peak response, R_p , does not necessarily occur when the load is directly over the point of interest.

In order to find the peak response at y , we need to find the maximum response for all $F(x)$.

$$\begin{aligned} R_p(y) &= \text{Max}[R(y, x)] \\ &= \text{Max}[\rho(y - x) F(x)] \end{aligned}$$

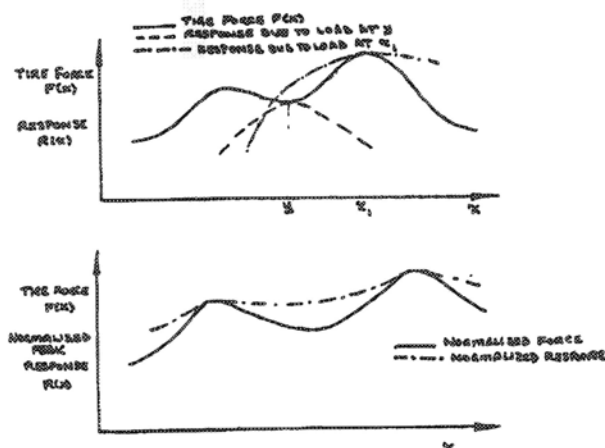
Taking the derivative of $R(x, y)$ with respect to x yields

$$\frac{\partial R(x, y)}{\partial x} = \rho(y - x) \frac{\partial F(x)}{\partial x} - F(x) \frac{\partial \rho(y - x)}{\partial x} \quad (14)$$

In general for $\frac{\partial F(x)}{\partial x} \neq 0$, $\frac{\partial R(x, y)}{\partial x}$ can only be

zero if $y \neq x$ because $\frac{\partial \rho(0)}{\partial x} = 0$.

Figure 10a shows graphically why the peak response may not occur when the load is directly over the point of interest. The peak response at y occurs when the load is at $x = x_1$, and not at $x = y$. The net effect of the influence function is to filter out troughs in the force profile, as shown in Figure 10b. The broader the influence function is, the greater the filtering effect. Since the road damage is related to $E[R_p^n]$, the effect of a broader influence



Graphical explanation of influence function effect
FIGURE 10

function is to increase the damage corresponding to the particular pavement distress.

The tire force is generally assumed to have a Gaussian distribution. Sweatman's experimental work (3) showed that this was a good approximation. We now assume that the peak response along the pavement also has a Gaussian distribution. Thus, for the case of rutting,

$$\Phi_R \propto E [R_p^4] \quad (15)$$

or,

$$\Phi_R \propto E[R_p]^4 (1 + 6.s^2 + 3.s^4) \quad (16)$$

where s is the coefficient of variation of peak compressive strain at the top of the sub-grade.

$$s = \frac{\sigma R_p}{E [R_p]} \quad (17)$$

For the case of cracking (10),

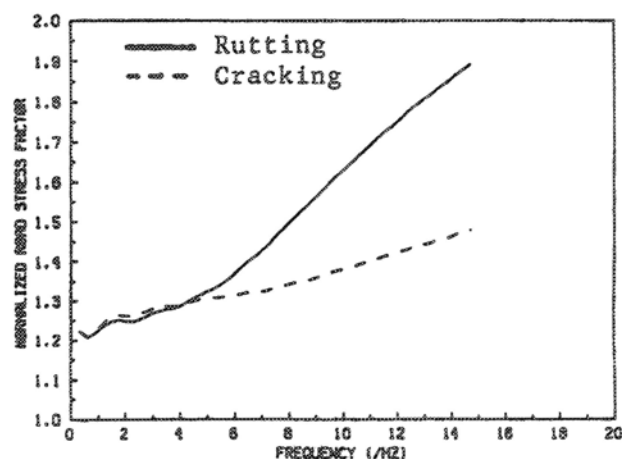
$$\Phi_C \propto E[R_p^5] \quad (18)$$

or,

$$\Phi_C \propto E[R_p]^5 (1 + 10.s^2 + 15.s^4) \quad (19)$$

where s is the coefficient of variation of peak longitudinal tensile strain at the bottom of the surface layer.

The above results are similar to Sweatman's Road Stress factor (3), except we now look at the statis-



Road stress factor as a function of load frequency
FIGURE 11

tics of the relevant primary response, not the tire force.

The effect of increasing the frequency content in the load is similar to broadening the influence function. To bear out this point, the effect of varying the frequency, of an applied load of the form

$$F(x) = 1 + a \sin(\omega x/v) \quad (20)$$

is investigated, where v is the speed of the load.

Figure 11 (10) shows how the road stress factor varies with frequency of applied loading for both rutting and cracking. It is clear that the rutting failure mode is more sensitive to frequency changes than cracking.

It is interesting to note that the effect of increasing vehicle speed, v , is similar to decreasing the width of the influence function because the spatial frequency, Ω , is inversely proportional to v ($\Omega = \omega/v$). (We note that the variance of the applied load also changes with velocity).

TANDEM AXLES

The concept of influence function is readily extended from single axles to tandem axles based on the assumption that the pavement is linear and that the superposition principle may thus be invoked. The total response at y will be made up of a contribution from each wheel load (9). Thus,

$$R(y, F_1(x), F_2(x+d)) = F_1(x) \rho(y-x) + F_2(x+d) \rho(y-x-d) \quad (21)$$

where ρ is the normalized influence function, d is the tandem axle spacing, and F_1 and F_2 are the forces at the tire-road interfaces of the front and rear axles, respectively. As in the case of the single axle, we consider the cases of both constant and dynamic moving loads, so as to give insight into the primary damage-causing forces.

Constant Moving Loads

In the case of a moving vehicle $x = vt$ then

$$R(y, F_1(vt), F_2(vt+d)) \rho(y-vt) + F_2(vt+d) \rho(y-vt-d) \quad (22)$$

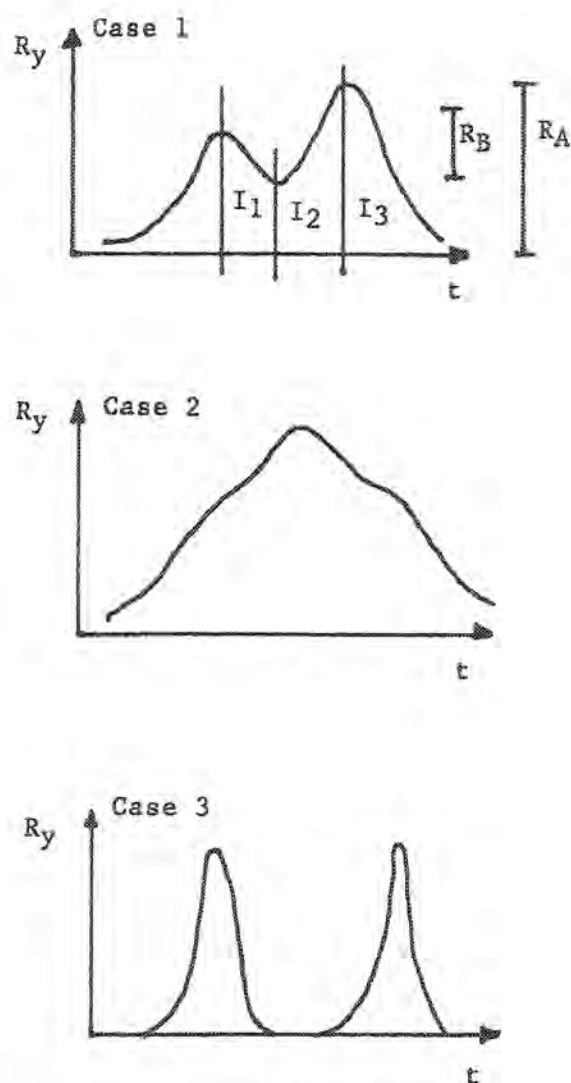
If $F_1 = F_{10}$ and $F_2 = F_{20}$, then

$$R_y = R_y(y, F_1, F_2)$$

$$= F_{10} \rho(y-vt) + F_{20} \rho(y-vt-d)$$

Depending on the shape of the influence function and the tandem axle spacing, the response at y as a function of time may have any of 3 forms shown in Figure 12.

- (1) Double Pulse
- (2) Single Pulse
- (3) Two Single Pulses



Response at a point due to pass of a constant load tandem axle

FIGURE 12

Case (1) is the most general case. The contribution to the total pavement degradation due to this double pulse is not two cycles of amplitude R_{01} and R_{02} , but rather a cycle of amplitude R_A and a cycle of amplitude R_B . If the axles are close together and the influence function is relatively broad, then the response at a point y is that of Case (2) above. Case (3) is the case when a tandem axle pass reduces to two single axle load applications. Thus, from the point of view of pavement damage prediction, the axles may be treated separately. This is true when the tandem axle spacing is large. This is also the case for the cracking damage mode, because the influence function of the corresponding primary response (top-layer longitudinal tensile strain) is narrow.

If the tandem has perfect load sharing then $F_{10} = F_{20}$. For rutting the total road stress factor for the constant load tandem is, assuming a fourth power law,

$$\Phi_R \propto E[R_A^4] + E[R_B^4]$$

$$\propto F_0^4 [(1 + \rho(d/2))^4 + (1 + \rho(d/2) - 2\rho(d/2))^4] \quad (23)$$

Case (1) reduces to Case (3) if $\rho(d/2) = 0$ and the axles loads are independent from the point of view of road damage. For case (2) the peak response will be

$$R_p = 2 F_0 (\rho(d/2))$$

then

$$\Phi_R \propto 16 F_0^4 (\rho(d/2))^4 \quad (24)$$

For the case where $F_{10} \neq F_{20}$, the damage increases significantly if the total weight on the axle, ($W = F_{10} + F_{20}$), is constant. Using Sweatman's definition for the Load Sharing Coefficient (LSC) (24) for this case we have

$$F_{10} = \frac{W}{2} LSC \quad (25)$$

and

$$F_{20} = \frac{W}{2} (2 - LSC)$$

For rutting the damage increases like $(2 - LSC)^4$. This fact is discussed in the results section.

Dynamic Moving Loads

The general response at a point y as a function of time is shown in Figure 13. For the case shown the damage will be given by (see part II of this paper):

$$\Phi = E[R_A^4] + E[R_B^4]$$

where

$$R_A = \text{Max}[R_p]$$

$$R_B = I_1 - I_2 \quad (26)$$

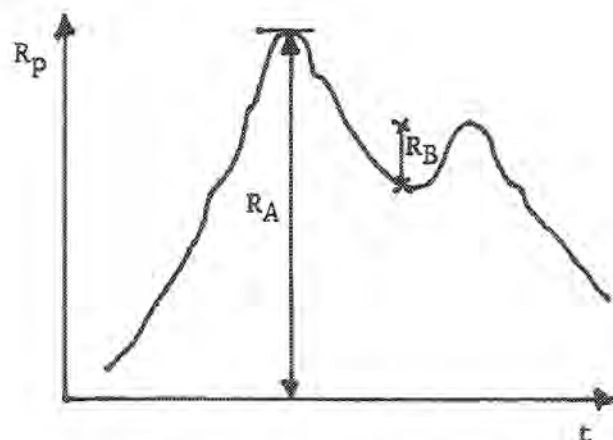
The road damage depends on the statistics of the primary (R_A) and secondary (R_B) pulses. For rutting we may write

$$\begin{aligned} \Phi_R &= E[R_A]^4 (1 + 6s_{R_A}^2 + 3s_{R_A}^4) \\ &+ E[R_B]^4 (1 + 6s_{R_B}^2 + 3s_{R_B}^4) \end{aligned} \quad (27)$$

and for cracking

$$\begin{aligned} \Phi_C &= E[R_A]^5 (1 + 10s_{R_A}^2 + 15s_{R_A}^4) \\ &+ E[R_B]^5 (1 + 10s_{R_B}^2 + 15s_{R_B}^4) \end{aligned} \quad (28)$$

For different pavements and different seasons the influence function for a particular primary response may vary. Also the dynamic wheel force statistics vary with road roughness. Thus a different road stress factor may be found for each condition. The approach taken in this paper is to compare the relative damaging effects of various



General response at a point due to pass of a tandem axle

FIGURE 13

suspension designs by comparing the relative damage caused by an axle due to a change in a vehicle parameter.

TIRE-FORCE REPRESENTATION

The tire force profile has generally been considered as a gaussian random variable, and as such may be characterized by a mean, a variance and an autocorrelation function or power spectral density. These characterizations have been used extensively in other areas of vehicle dynamics. In our problem, we want the most efficient way of accurately reproducing the tire force for pavement primary response calculation.

For certain vehicle and pavement conditions the force characterization may be straight forward. If the tire load is dominated by the sprung mass bounce and pitch modes (typically between 1 and 4 Hz), and there is little contribution from the wheel mode (typically 10 Hz) or if the pavement type is such that it's main failure mode is surface cracking, i.e., it fails due to cracking long before rutting becomes significant, then the effect of the influence function will be small and the peak response at any point, R_p , in the pavement will be directly proportional to the load overhead.

Thus

$$E[R_p] \propto E[F] \quad (29)$$

and

$$VAR[R_p] \propto VAR[F]$$

In this case load characterization suggested by Sweatman (3) may be used. All that is necessary to predict is the primary response statistics (assuming a gaussian tire force distribution) is the mean and dynamic load coefficient. Sweatman (3) found that the DLC of the tire force was well correlated with the vehicle speed and the square root of the roughness, i.e.,

$$DLC = K_v \sqrt{r} \quad (30)$$

Sweatman (3) found that the mean dynamic tire force may be different to the static tire force by up to 5% for various reasons:

- 1) The pavement crown causes a lateral shift of load from the inner to the outer wheel paths. This is also true when going up or down hills.
- 2) Aerodynamic lift

- 3) In tandem drive axles, interaxle load transfer will occur due to drive torque reaction, and non-symmetric suspension geometry and stiffness.

In the general case where the influence function non-linear 'filtering' effect is important, an efficient load characterization technique is difficult. Various approaches are suggested here:

- 1) The simplest way is to transfer the raw load profile of each axle for various roughnesses in full digital form.
- 2) The force profile $(F(x))$ may be approximated by a periodic function or sums of periodic functions.
- 3) Express the relevant slope information in closed form, e.g. autocorrelation function.

The first technique while being the most accurate is inefficient, as it entails the transferring of large data files, however it is the method used in this paper.

PARAMETRIC STUDIES

The effect of varying the following vehicle parameters have been studied (10):

- Suspension Type
 - Four-Leaf Tandem
 - Walking-Beam Tandem
 - Air-Spring Tandem
- Suspension Stiffness, k_s
- β -parameter for Leaf-Springs
- k_1/k_2 for Leaf-Springs
- Shock Absorber Damping for Air-Springs
- Tire Pressure
- Axle Load Sharing Coefficient
- Tandem Axle Spacing

The effect of varying the different suspension parameters are compared to a standard tandem

axle. The standard tandem axle was taken to be a four-leaf spring drive tandem, whose specifications are given earlier in this paper. Damage is calculated using a modified version of VESYS IIIA. In order to examine the effects of changing vehicle parameters on different pavement failure modes, equivalency factors, EF_j , are defined for each of cracking, rutting and per cent serviceability.

$$EF_j = \frac{\text{Damage due } j^{\text{th}} \text{ axle}}{\text{Damage due standard axle}}$$

$$= \frac{N_f}{N_{fj}}$$

where N_f is the number of cycles to failure for a particular damage mode. The failure criterion used are:

Rutting	RD = 0.6 in
Cracking	AC = 50%
Serviceability	PSI = 2.5

RESULTS

Effect of β -Parameter

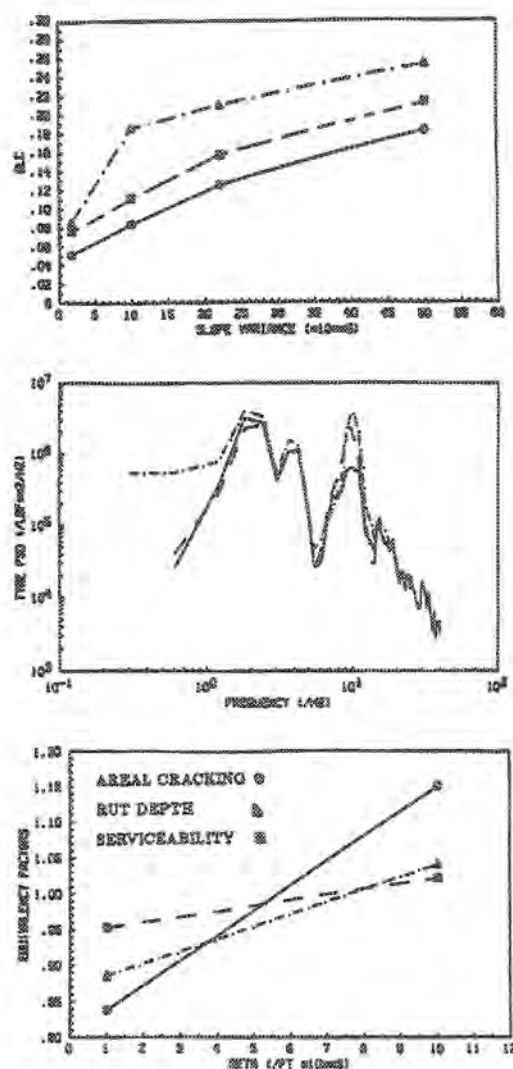
β is a friction parameter (see equation (1)), which describes the hysteretic nature of the leaf-spring. Figure 14 shows the effect of varying β on the four-leaf spring suspension behaviour. The nominal value of β is 4×10^{-3} feet and it was varied from 1×10^{-3} feet to 10×10^{-3} feet. It is interesting to note that the DLCs at low slope variances are relatively large. For linear systems we expect the DLC to be proportional to $\sqrt{SV}$. Because of the leaf-spring characteristics, it acts like a lightly damped system at low amplitude excitation, and a more heavily damped system for large excitations. Thus, the DLC vs. SV plot increases rapidly at first, and then rises more slowly.

Figure 14c indicates how changing the β -parameter affects pavement performance as predicted by VESYS. Varying β between 1×10^{-3} and 10×10^{-3} feet indicates that cracking increases by 31% and rutting by 14%. The serviceability (on which the AASHTO equivalency factors are based) decreases by 6.5%.

Effect of k_1/k_2

Figure 15 shows the effect of varying k_1/k_2 , the ratio of the slopes of the leaf-spring envelopes, on pavement dynamic loading.

The nominal value of k_1/k_2 is 1.5 and it is varied between 1.25 and 2.0. The results indicate that as k_1/k_2 is increased the dynamic loading decreases. This is consistent with the fact that the friction in the leaf-spring is related to $k_1 - k_2$. It is interesting to note that there is little change in the DLC as changes from 1.5 to 2, indicating that truck designers need not increase k_1/k_2 above 1.5.



- Leading drive axle DLC versus SV
 - Leading drive axle tire force PSD at $SV = 50 \times 10^{-6}$
 - Effect of varying β -parameter on pavement response
- - - $\beta = 1.0 \times 10^{-3}$ ft
 — $\beta = 4.0 \times 10^{-3}$ ft (standard)
 . . . $\beta = 10.0 \times 10^{-3}$ ft

Effect of β parameter on vehicle response

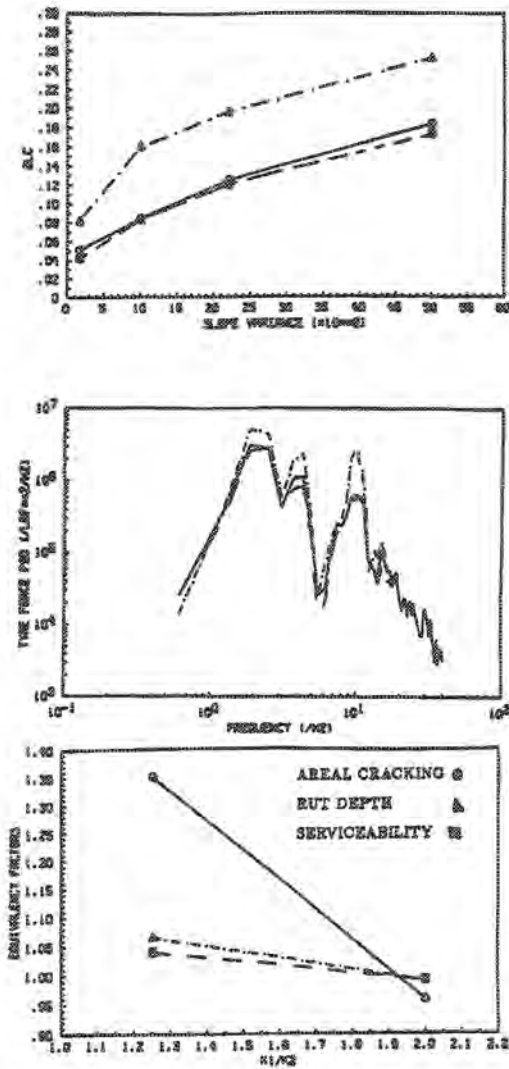
FIGURE 14

Figure 15c, shows that in changing k_1/k_2 from 1.5 to 2.0 cracking decreases by 5%, while rutting and serviceability show no noticeable change. Small values for k_1/k_2 (1.25) increases damage substantially. Cracking increases by 35%, while rutting increases by 7%.

Effect of Tire Pressure

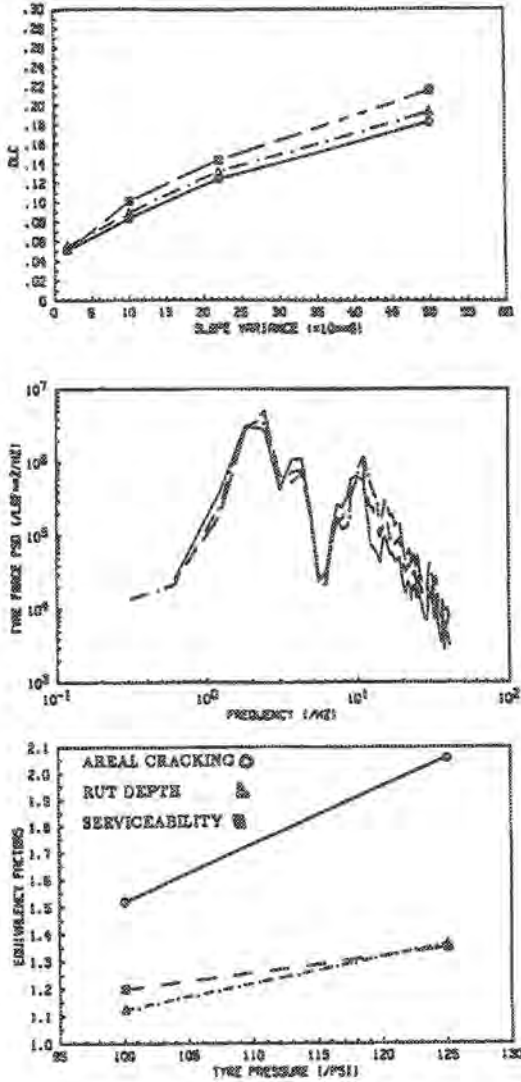
The effect of truck tire inflation pressure on flexible pavement performance was investigated. The ef-

fect of increasing tire inflation pressure is to increase the tire spring constant and to decrease the average area of the contact patch, hence increasing the average contact pressure. The effect of tire pressure changes on the vehicle response is not very significant. For a pressure variation from 75 psi (nominal) to 120 psi, the DLCs of the lead axle in the drive axle group change from 0.12 to 0.14 at $SV = 22 \times 10^{-6}$.



- a) Leading drive axle DLC versus SV
 - b) Leading drive axle tire force PSD at $SV = 50 \times 10^{-6}$
 - c) Effect of k_1/k_2 on pavement response
- - - $k_1/k_2 = 1.25$
 — $k_1/k_2 = 1.5$ (standard)
 - - - $k_1/k_2 = 2.0$

Effect of k_1/k_2 on vehicle response
FIGURE 15



- a) Leading drive axle DLC versus SV
 - b) Leading drive axle tire force PSD at $SV = 50 \times 10^{-6}$
 - c) Effect of tire pressure on pavement response
- TP = 75 psi (standard)
 - - - TP = 100 psi
 - - - TP = 125 psi

Effect of tire pressure on vehicle response
FIGURE 16

Examination of Figure 16c, shows that road damage is affected significantly by tire pressure. This is primarily due to the effect of changing the contact area. Cracking is shown to be highly sensitive to tire pressure; tire pressures of 120 psi are twice as damaging as those of 75 psi. The effect on rutting does not appear to be so dramatic. It is important to realize that about 80% of the rutting is due to subgrade permanent deformation, which is insensitive to tire pressure, as the induced compressive stresses do not change significantly. However the surface layers undergo much greater strains, because of increased contact pressure. Thus, while the total rutting increases by 30%, the increase in the permanent deformation of the surface layers increases by approximately 300%.

Effect of Leaf-Spring Stiffness

The effect of varying the average leaf-spring stiffness,

$$\left(\frac{K_1 + K_2}{2} \right)$$

on vehicle response is shown in Figure 17. Figure 17a shows that increasing the nominal spring constant (60,000 lb/ft) by 50% increases the DLC at SV = 22 x 10 from 0.125 to 0.180. The DLC for a 50% decrease in spring stiffness is 0.09. Figure 17b shows that the main effect of changing the spring constant is to attenuate the contribution of the body mode in the tire force. Cracking changes significantly over the range of stiffness considered because it is highly dependent on the variance of the response.

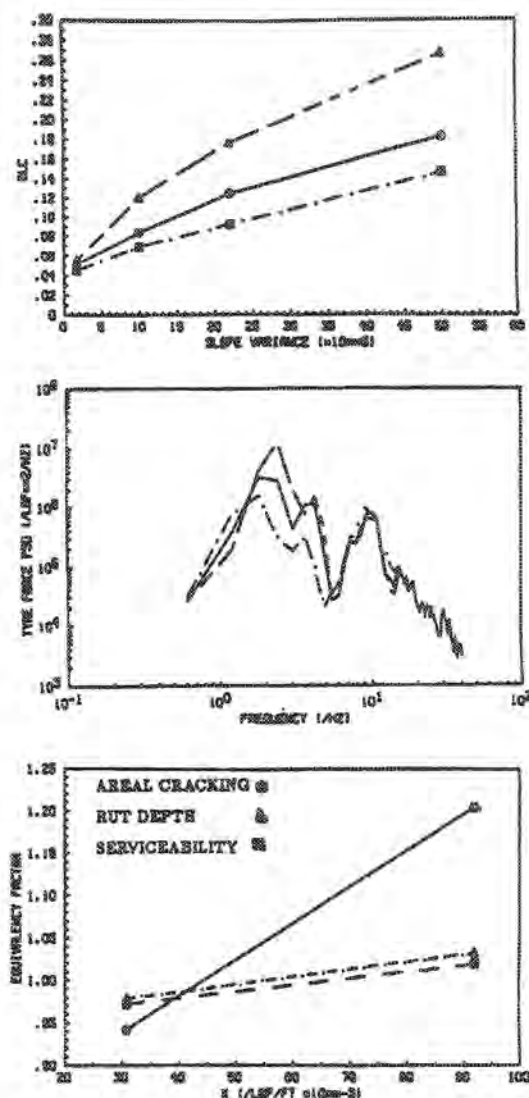
Effect of Axle Spacing

The effect of axle spacing in the four-leaf tandem axle group is shown in Figure 18. It is apparent that the effects on dynamic pavement loads for axle spacing varying from 44" to 60" is small. (The nominal spacing is 48"). The larger axle spacings cause the vehicle body modes to be excited more, with a corresponding increase in DLC. This leads to an increase in cracking, because of the narrow influence functions associated with longitudinal strain in the surface layer. Rutting, on the other hand decreases dramatically with increasing axle spacing, because the increase in DLC is offset by the decrease in the addition of the compressive strains in the pavement. The results show that increasing spacing from 48" to 60" decreases rutting by 27%.

Effect of Suspension Type

Figure 19 shows the effect of suspension type with typical parameters. The walking beam leaf-spring

suspension has the highest DLCs, the air-bag suspension the lowest, and the four-leaf-spring suspension in between. Comparison of the tire force power spectral densities indicates that the walking-beam suspension has significant power at 10 Hz, corresponding to the bogie pitch mode



- Leading drive axle DLC versus SV
- Leading drive axle tire force PSD at SV = 50 x 10⁻⁶
- Effect of leaf spring stiffness on pavement response

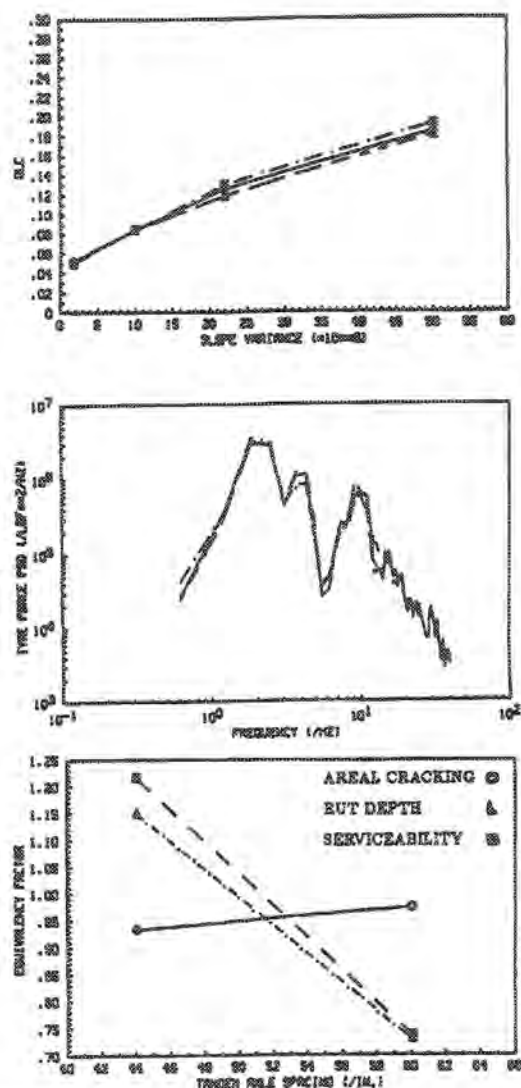
--- K = 30,600 lb/ft
 — K = 61,200 lb/ft (standard)
 --- K = 91,800 lb/ft

Effect of leaf spring stiffness on
 vehicle response

FIGURE 17

which has very little damping (1). The shock-absorbers on the air-springs damp out the wheel mode oscillation. It is interesting to note that the walking-beam has the lowest body mode power of the three suspensions. This is due to the effects of wheel-base filtering (1).

Figure 19c shows that the walking-beam suspension causes 10.5% more cracking, 2.3% more rutting and a 4.7% decrease in serviceability, when compared to the equivalent four-leaf-spring suspension. The air-bag, on the other hand, causes 5.8% less cracking, 3.2% less rutting, and a 9.2% change in serviceability.

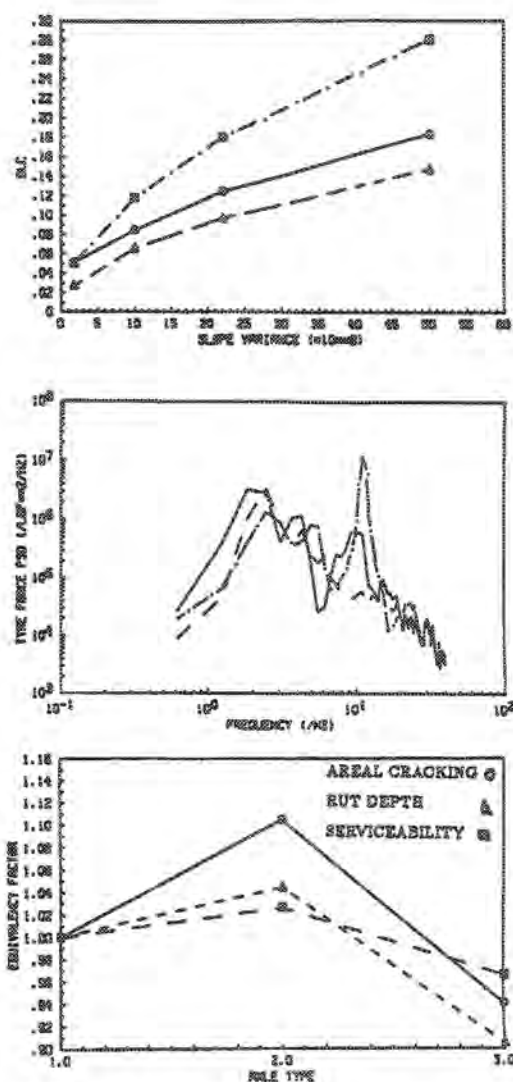


- a) Leading drive axle DLC versus SV
- b) Leading drive axle tire force PSD at $SV = 50 \times 10^{-6}$
- c) Effect of axle spacing on pavement response

---- Spacing = 44 inches
 — Spacing = 42 inches (standard)
 - * - Spacing = 60 inches

Effect of axle spacing on vehicle response

FIGURE 18



- a) Leading drive axle DLC versus SV
- b) Leading drive axle tire force PSD at $SV = 50 \times 10^{-6}$
- c) Effect of suspension type on pavement response

— Axle 1: Four-leaf spring tandem
 - * - Axle 2: Walking beam
 ---- Axle 3: Air-spring tandem

Effect of suspension type on vehicle response

FIGURE 19

Effect of Load Sharing Coefficient (LSC)

The interaxle load transfer is characterized by the Load Sharing Coefficient (LSC) discussed in (3). In order to investigate the effects of a non-symmetric load distribution the tandem axle four-leaf spring lengths were varied while keeping the total axle-group load constant. Figure 20 shows the DLCs

and tire force PSDs of the leading axle in the graph for different LSCs. It is interesting to note that the DLC of the lighter axle increased while that corresponding to the heavier axle decreased.

Figure 20c shows that road damage is very sensitive to the LSC. The axle group with the LSC of 0.8 causes 23% more cracking, 43% more rutting, and a 37% decrease in serviceability, when compared to the optimum load sharing condition (LSC = 1). Clearly, the load sharing effectiveness of tandem suspensions deserves close attention from vehicle designers.

Effect of Shock Absorber Damping

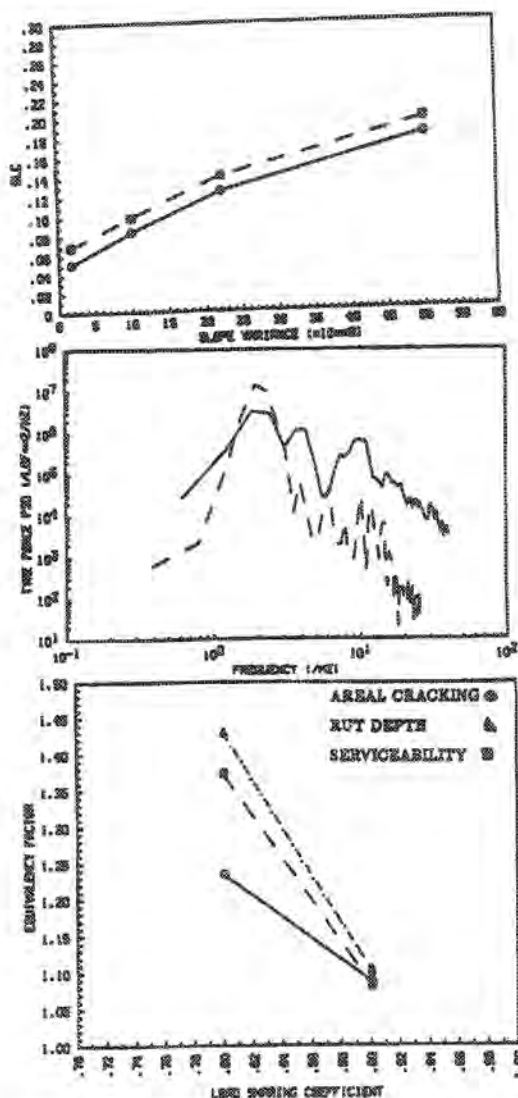
The effect of varying shock absorber damping on air-spring suspensions was examined. As illustrated in Figure 21, DLCs decrease with increasing damping. Figure 21c shows the equivalency factors for the various damage modes. Damage can be reduced by 8.1% by increasing the damping.

Comparison of Road Stress Factor to Modified VESYS IIIA Predictions

In order to compare the Modified Road Stress Factor with the predictions from the modified VESYS IIIA, we look at the relative change in cracking and rutting for varying . In the comparison it is important to realize that the VESYS predictions compare the number of load applications to reach a certain damage criterion, hence using the average load dynamics over the pavement life, whereas the road stress factor can only compare axles for a given road roughness, season number (influence function etc). Figure 22 shows the rutting and cracking indexes for various roughness. The index is the RSF normalized by the damage predicted by a single axle carrying the average axle load. Comparing indices for various indicates that rutting increases by about 10%, and cracking by 20% for varying between 1.5 and 1.25, while rutting decreases by 1.5% and cracking by 2% for equal to 2.0. While not exactly replicating VESYS, similar trends are observed.

CONCLUSIONS

This paper has reported on research results from an on-going USDOT/FHWA research project. Detailed heavy truck dynamic simulation programs have been developed, and significant modifications have been made to an existing flexible pavement program (VESYS IIIA) to account for dynamic tire loads due to single and tandem axles. The results of this paper have shown that:

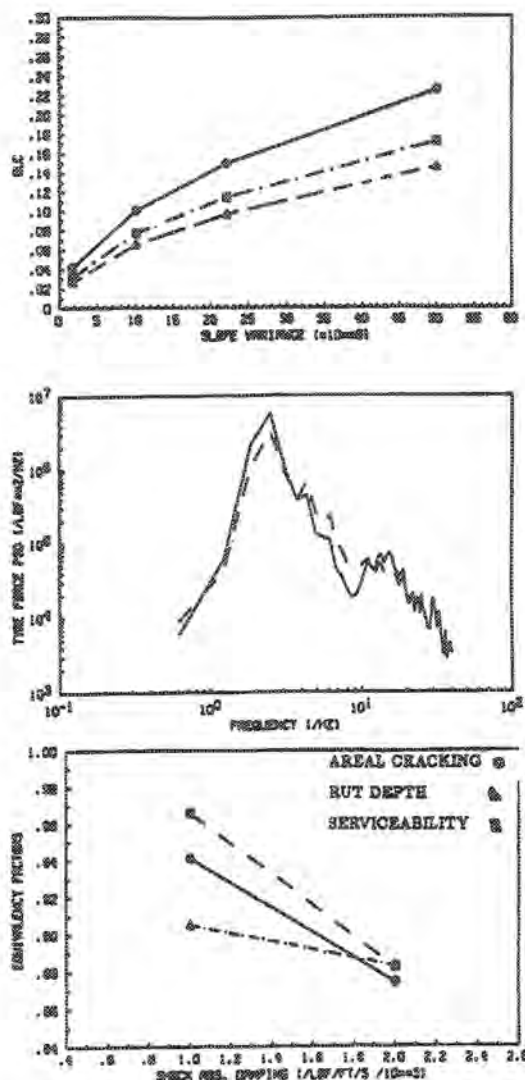


- Leading drive axle DLC versus SV
- Leading drive axle tire force PSD at $SV = 50 \times 10^{-6}$
- Effect of LSC on pavement response

— LSC = 1.0 (standard)
 --- LSC = 0.9
 - * - * LSC = 0.8

Effect of load sharing coefficient on vehicle response
 FIGURE 20

- Dynamic pavement loads have a significant impact on pavement damage.

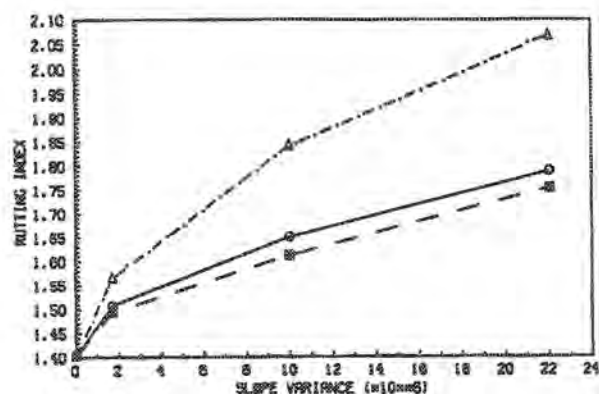


- a) Leading drive axle DLC versus SV
- b) Leading drive axle tire force PSD at $SV = 50 \times 10^{-6}$
- c) Effect of shock absorber damping on pavement response

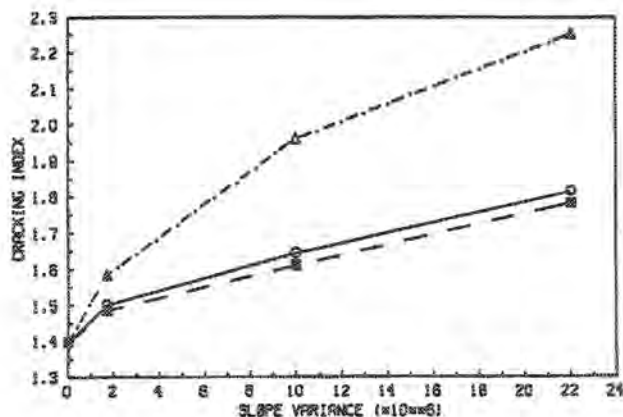
— 1,000 lbf/ft/s rebound 250 lbf/ft/s compression (standard)
 - - - 500 lbf/ft/s rebound, 125 lbf/ft/s compression
 - - - 2,000 lbf/ft/s rebound, 500 lbf/ft/s compression

Effect of shock absorber damping on vehicle response
 FIGURE 21

- Pavement damage may be reduced significantly by careful suspension design.
- Air-bag suspensions were found to be the least damaging suspension, while the walking beam was found to be the most damaging.
- A modified Road Stress Factor was introduced to more accurately reflect rutting and cracking damage. Comparisons with a more detailed VESYS IIIA are reasonable.



a) Rutting index versus SV for various k_1/k_2



b) Cracking index versus SV for various k_1/k_2

- - - - $k_1/k_2 = 1.25$
 — $k_1/k_2 = 1.5$
 - - - - $k_1/k_2 = 2.0$

Modified road stress factor (index) versus slope variance
 FIGURE 22

ACKNOWLEDGEMENT

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