Effects of Dynamic Loads on Performance of Asphalt Concrete Pavements

JORGE B. SOUSA, JOHN LYSMER, SHI-SHUENN CHEN, AND C. L. MONISMITH

To determine the influence of dynamic loading on pavement response, an analytical and a laboratory study were undertaken. In the analytical study, temporal and spatial variation of stresses and deformations in a pavement system, resulting from dynamic loading conditions, were estimated using the computer program SAPSI. To compute these stresses and deformations, elastic and damping characteristics of various materials constituting pavement sections were defined by a laboratory investigation that provided such data for an asphalt concrete (AC) and a fine-grained soil (silty clay) for a limited range in service conditions. With the SAPSI program, a representative pavement system consisting of an AC layer resting directly on silty clay subgrade was analyzed to determine the pavement life that might result using actual load histories for three tandem-axle suspensions as compared to that obtained for the same axle with a uniform static load. Results of the dynamic analyses suggest that pavement life is reduced when dynamic effects are considered, and the magnitude of reduction is dependent on the tandem-axle suspension. The largest reduction in pavement life was obtained for the axle with the walking beam suspension. Comparable smaller reductions, as compared to the static case, were obtained for the torsion bar and four-leaf spring suspensions.

Assessment of pavement response to dynamic loads requires the following information:

1. Time history and spatial distribution of loads that specific vehicles apply to the pavement as a function of vehicle speed and pavement profile.
2. Solutions for stresses, strains, and deformations of representative pavement structures subjected to loads that duplicate those applied in-situ both in magnitude and as functions of time.
3. Measures of the dynamic response of the materials constituting pavement systems over the range in loading times, stress states, and material states that might be anticipated.

Many studies have been conducted on the effects of dynamic loads of trucks on pavements. Recent investigations have included: evaluation of theoretical vehicle models; in-situ measurements of dynamic loads resulting from special trucks or from truck loads passing over bumps, or other predefined obstacles; and the measurement of dynamic loads by special instrumentation mounted on the trucks themselves. This paper provides a brief summary of some of those investigations to provide the background for the methodology described herein for estimating the influence of dynamic loads on pavement response.

Department of Civil Engineering, Institute of Transportation Studies, University of California, Berkeley, Calif. 94720.

BACKGROUND

Truck Studies

Results of instrumented truck studies indicate that dynamic response of these vehicles is influenced by:

1. Suspension type (Figure 1 illustrates some examples of suspension systems);
2. Vehicle type; and
3. Load (the magnitude of the load on the vehicle as well as its center of gravity influence dynamic response).

Vehicle speed and pavement roughness also have significant influences on dynamic response. Figure 2 illustrates results obtained by Sweatman (*1*) which demonstrate the influence of suspension type as well as pavement roughness and speed on dynamic load coefficients.

The results reported by Sweatman (*1*) indicate that different suspensions exhibit different levels of dynamic response. For tandem axles the "walking-beam" type produced the greatest dynamic loads, and torsion-bar suspensions, with hydraulic absorbers, produced the least (e.g., Fig. 2). Other factors such as tire pressure and tire "out-of-roundness" also have some influence, but it appears that the primary factors affecting the response of dynamic wheel loads are suspension type, vehicle type, truck loading and its spatial distribution on the truck, pavement roughness, and vehicle speed.

Analysis of Truck-Pavement Interactions

It is possible to estimate the dynamic load caused by a particular truck if certain characteristics of the truck are known and the surface profile of the pavement on which it is operated has been defined. One such representation for the truck system is illustrated in Figure 3 and has been proposed by Lee (*2*). The experimental setup for the scale location is shown in Figure 4. Figure 5 illustrates the computed responses for the left dual wheels of the loaded truck of Figure 3 as it moved at 30 mph. Figure 5 also shows loads measured at specific points by weigh-in-motion (WIM) scales.

These results illustrate that it is possible to model dynamic response; however, model parameters such as those identified in Figure 3 must be available. The results in Figure 5 indicate

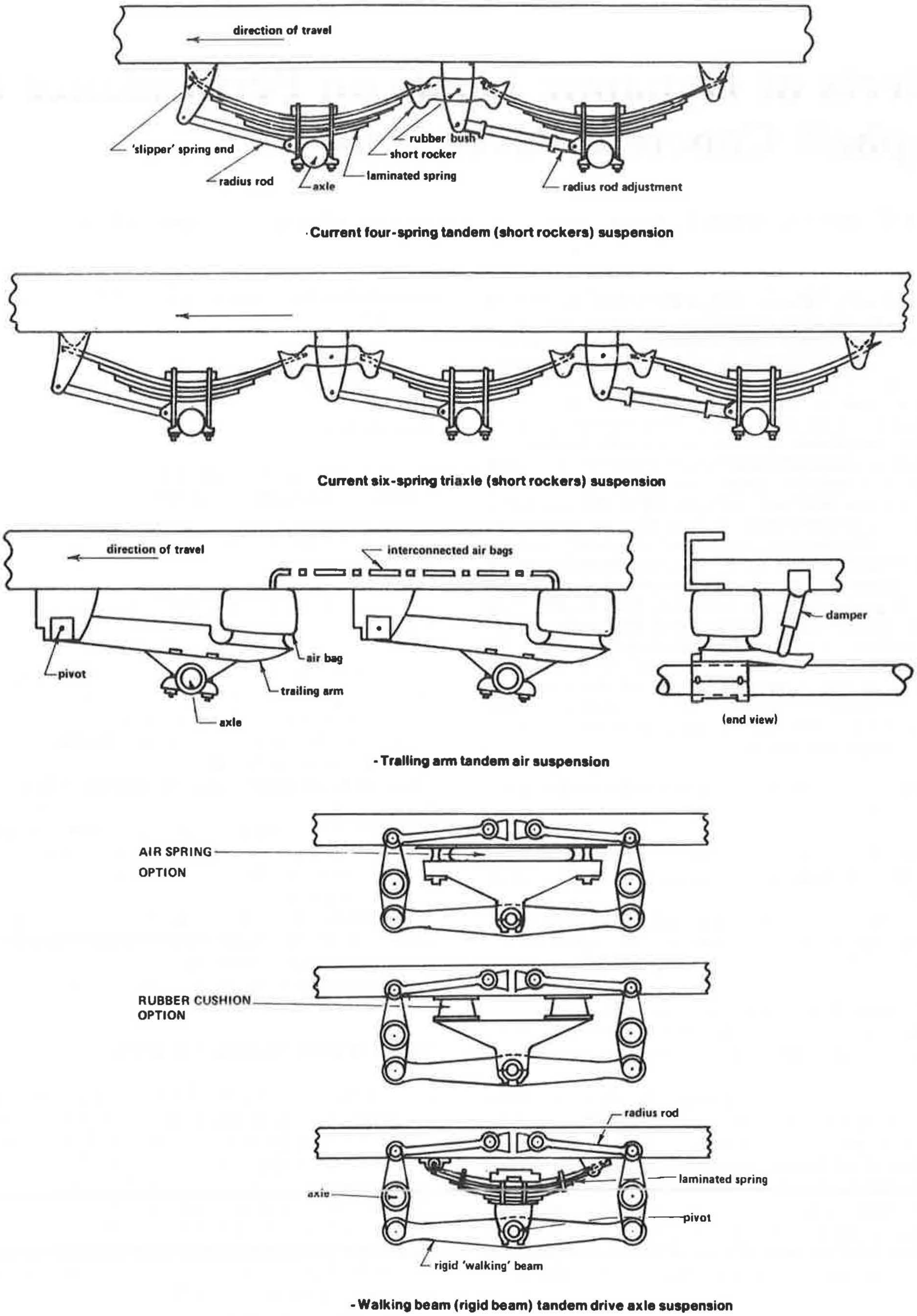
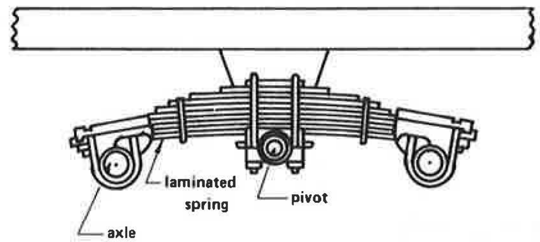
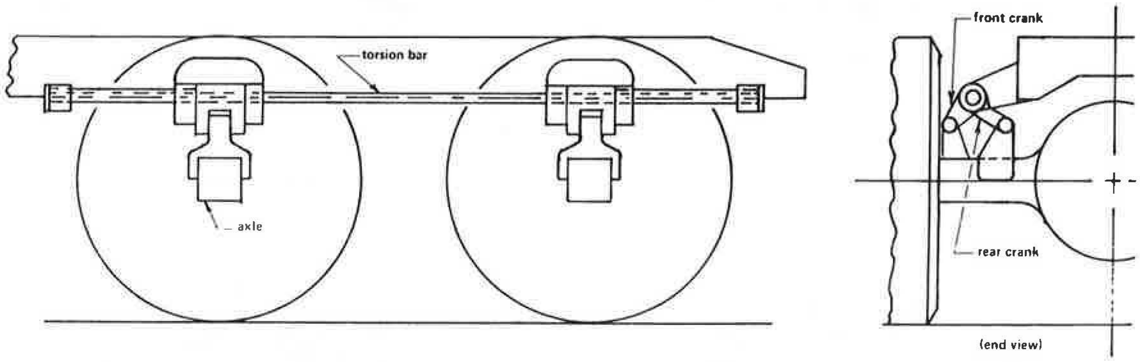


FIGURE 1 Commonly used truck suspensions (*1*).



— Single point tandem drive axle suspension



- Torsion bar tandem drive axle suspension

FIGURE 1 ***continued.***

that WIM systems may provide a check on any computational procedures used to define dynamic loads. However, since WIM devices provide measurements of dynamic loads only at specific points, WIM results do not provide a complete check on the loading that a particular vehicle exerts on a pavement.

Several researchers have provided estimates for the complete spectrum of dynamic loading (*3, 4*). Although loading frequencies can be developed from data such as those shown in Figure 5, it is possible to directly ascertain specific frequency ranges associated with different types of suspensions and vehicles (*5*). Figure 6 illustrates the results of such determinations; note that the frequencies are less than 20 Hz.

ANALYTICAL DEVELOPMENTS

Current capabilities to perform dynamic analyses are highly developed. However, the computational effort required to solve a completely general three-dimensional dynamic problem representative of a pavement system subjected to a moving load is very large—too large, in fact, to be acceptable for practical pavement analyses. This effort can be reduced through simplifying assumptions regarding material properties, the type and distribution of the dynamic loads, and the geometry of the problem. This section briefly discusses these efforts and the resulting computer solution termed SAPSI.

Material Properties

For this analysis, the materials constituting the pavement section have been assumed to be linear viscoelastic in response to loads. With this assumption, the laws of superposition are valid and, in turn, provide considerable computational advantages. Unfortunately, by choosing these material properties, it is not possible to directly obtain permanent displacements. It may, however, be possible to estimate them from the computed stress time histories.

An additional advantage of using viscoelastic materials in the computational models is that it leads to stable algorithms and computer codes. Furthermore, the description of the material properties is simple and unambiguous, and can directly utilize the data described subsequently.

Dynamic Loads

A major challenge to the development of an efficient method of dynamic analysis is the fact that actual traffic loads move over the surface of the pavement. Thus, one of the first theoretical tasks undertaken in this study was to investigate the effects of vehicle velocity on the stresses in a typical pavement. More specifically, an attempt was made to answer the question: "How different is the stress field developed under a moving load from the stress field developed under the same load acting at a stationary location?"

This problem has been investigated by Cole and Huth (*6*) for the special case of a vertical line load moving at constant velocity over the surface of a uniform elastic half space. They found that the major effect of the nonstationarity of the load is an increase of the maximum stresses that occur in the pavement. This increase can be closely approximated by the ratio:

$$\text{Amplification ratio} = \frac{\text{maximum dynamic stress}}{\text{static stress}} = \frac{1}{1 - (V/V_s)^2} \quad (1)$$

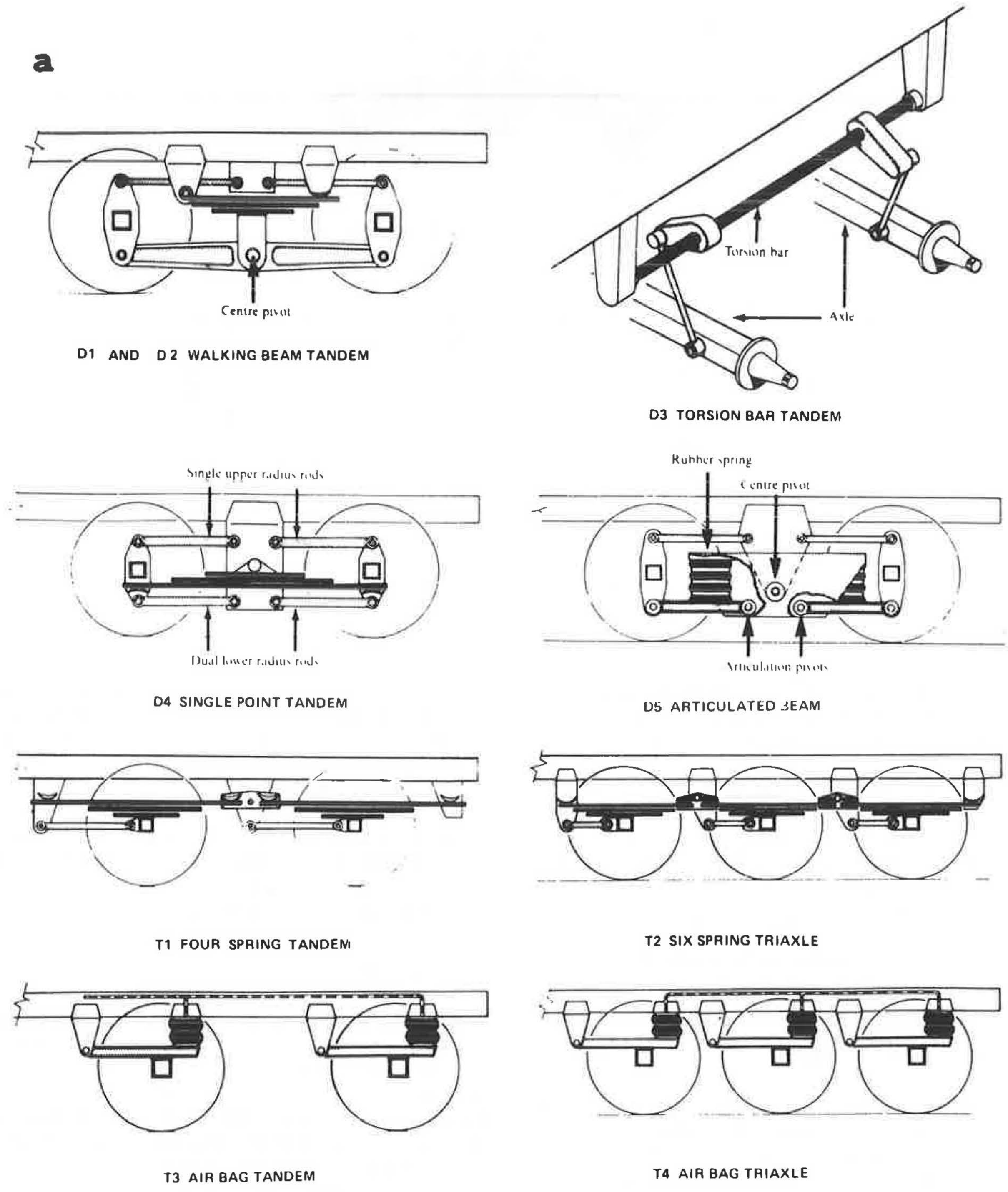


FIGURE 2 Factors influencing dynamic response: (a) suspension types tested for dynamic loading (*1*).

where

V = velocity of the moving load, and
V_s = shear wave velocity in the half space.

Unfortunately, the above result is not directly applicable to pavement structures, which behave like layered systems, and no solutions for such systems are available. It was, therefore, necessary to develop a new theory and an associated computer program, MOVE (*7*), for dynamic analysis of the layered system shown in Figure 7. The computational model consists of a number of viscoelastic layers resting on a rigid base, and the loading is a vertical line load that moves with a constant velocity, V, over the free surface of the system. A lower half-space can be simulated by placing the rigid boundary at a large depth.

The computer program was verified by comparing it with a static solution by Poulos and Davis (*8*), and also with the Cole and Huth (*6*) solution (where P_0 = 2,000 lb/ft, V_s =

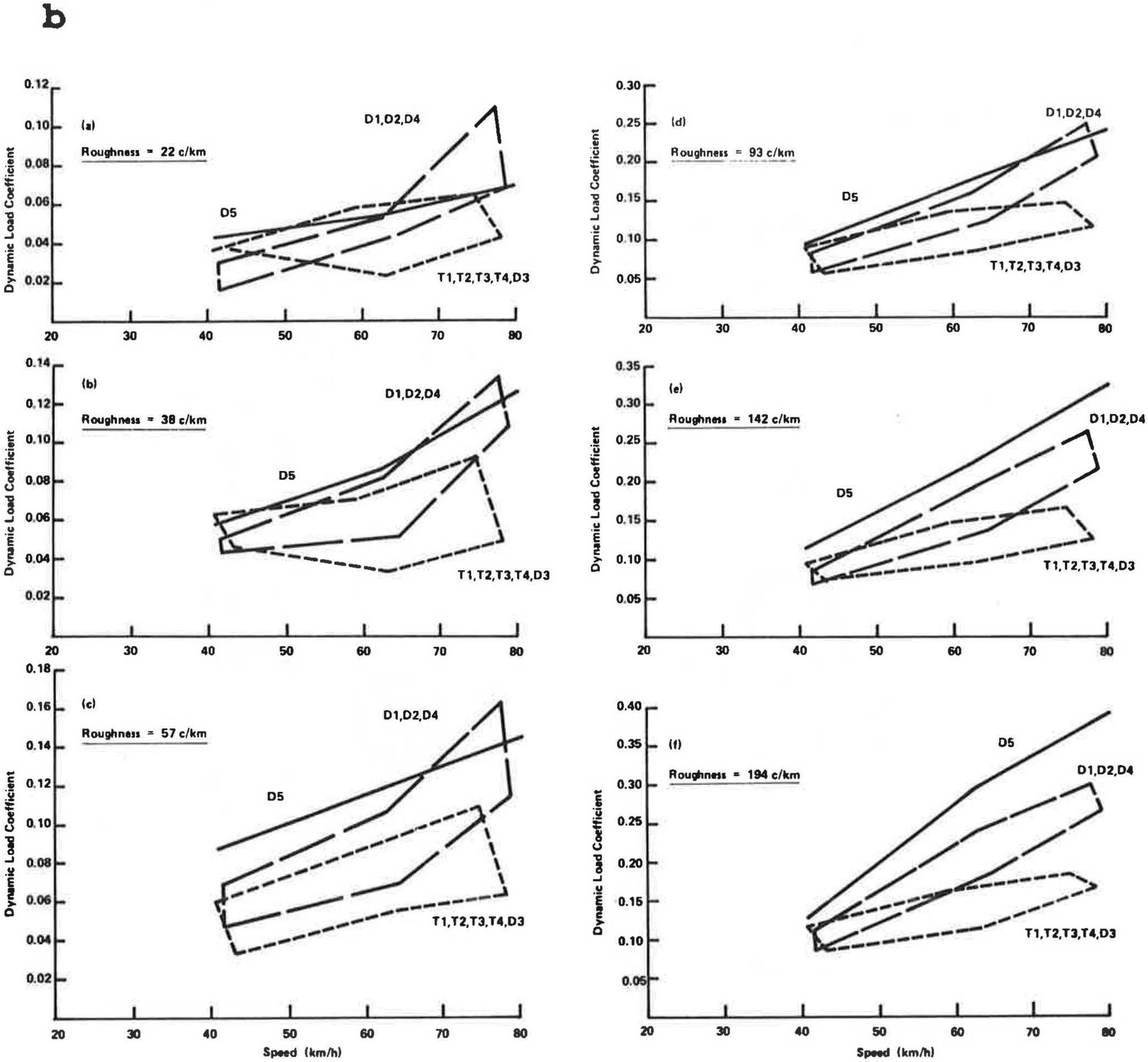


FIGURE 2 Factors influencing dynamic response: (b) effects of speed and pavement roughness on dynamic load coefficient for three groups of suspensions (*1*).

500 ft/sec, Poisson's ratio = 0.4, H = 30.0 ft). In both cases, excellent agreement was obtained (Tables 1 and 2). Following verification, several pavement structures were analyzed. The two-layer structure shown in Figure 8 is an example; it consists of an asphalt concrete layer 20-in. thick resting on a half-space subgrade. This model was analyzed for line loads moving with three different velocities: V = 0, 60, and 90 mph. For each case, the maximum shear stresses developed at different depths were computed. The values so obtained were compared to those resulting from a stationary load. Results of this analysis are shown in Figure 8 in the form of a plot of amplification ratio vs. depth. Also shown is the amplification ratio predicted by Equation 1, using the properties of the subgrade for the half space.

The results indicate that the Cole-Huth solution overestimates the importance of vehicle velocity. At a velocity of 60 mph, the amplification in the actual pavement is only 7 percent; and within depths that are of interest for analyses of subgrade stresses, it is less than 10 percent. These increases are relatively small so that a major computational effort does not seem appropriate for an accurate determination. Accordingly, the assumption has been made that the dynamic stresses in a pavement can be computed using stationary loads. It is also recommended that a small dynamic amplification factor thus neglected be included in the design by multiplying the stresses by approximate stress amplification factors obtained using the program MOVE. The savings in computation effort thus achieved can be significant.

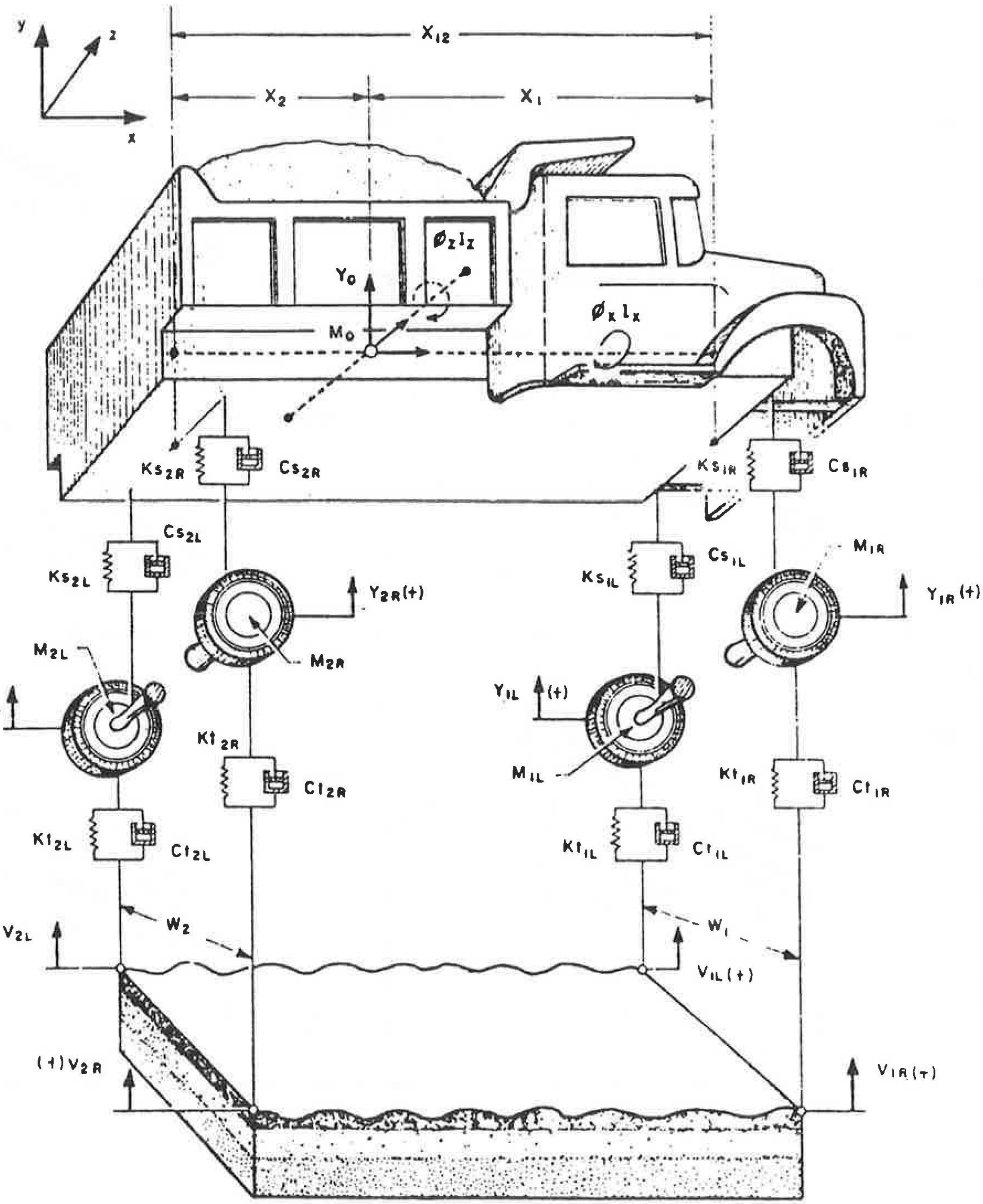


FIGURE 3 Truck elements used to estimate dynamic response (*2*).

The above conclusions and simplifying assumption should not be construed to mean that dynamic effects can be neglected or that the stresses in a pavement will be independent of the velocity of the traffic moving on the pavement. It can be assumed that wheel loads are stationary as to their location on the pavement, but the magnitude and time variations of these loads are strongly dependent on the type and velocity of the traffic and the stiffness and roughness of the pavement. Also, dynamic effects are likely to be significant for the manner in which stresses from different wheel loads superimpose in a pavement. That is, in computing the stress field caused by a group of wheels, dynamic effects may have to be considered.

The finding that all loads can be considered stationary is significant. It means that, provided the magnitude and time variation of typical wheel loads can be determined, relatively simple computer programs can be used for stress and distress analysis of pavements.

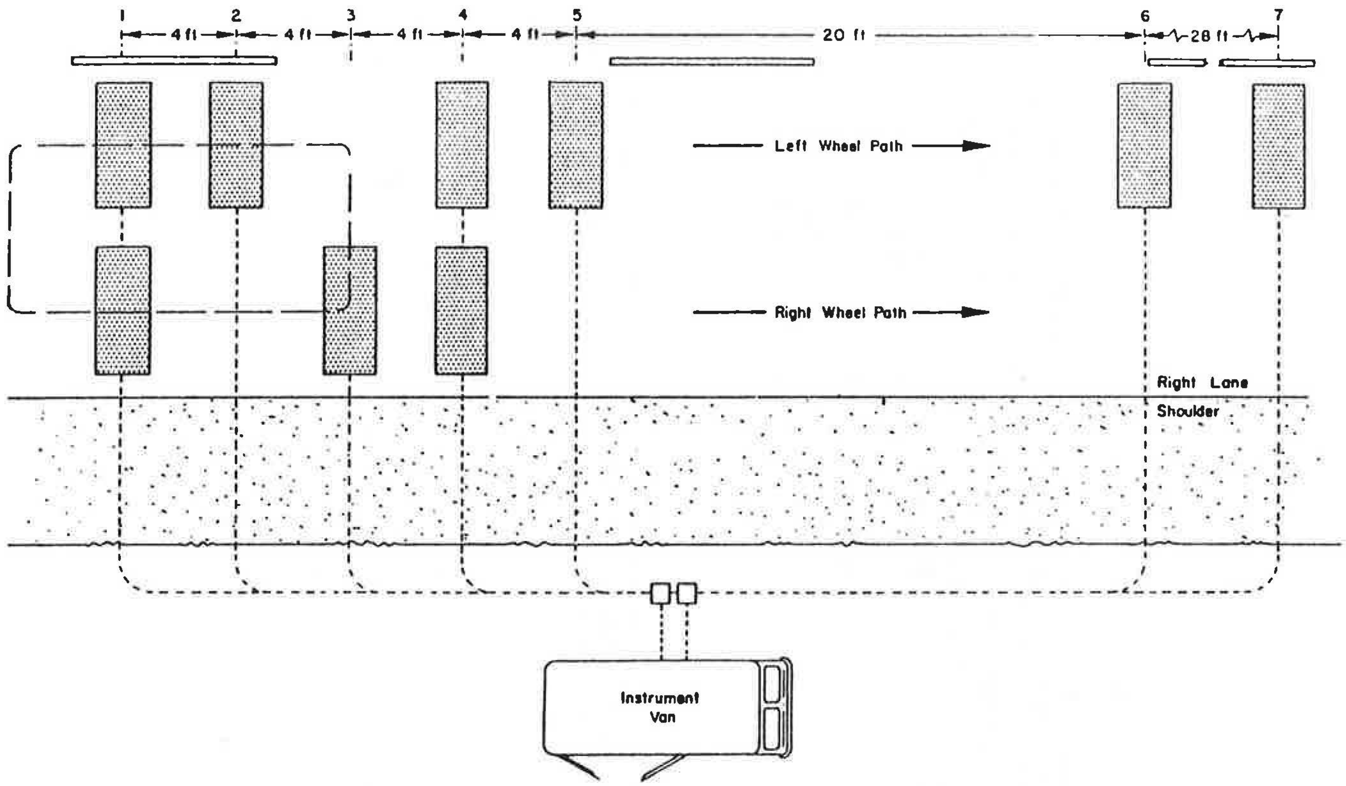


FIGURE 4 Weigh-in-motion installations to assess dynamic response (*2*).

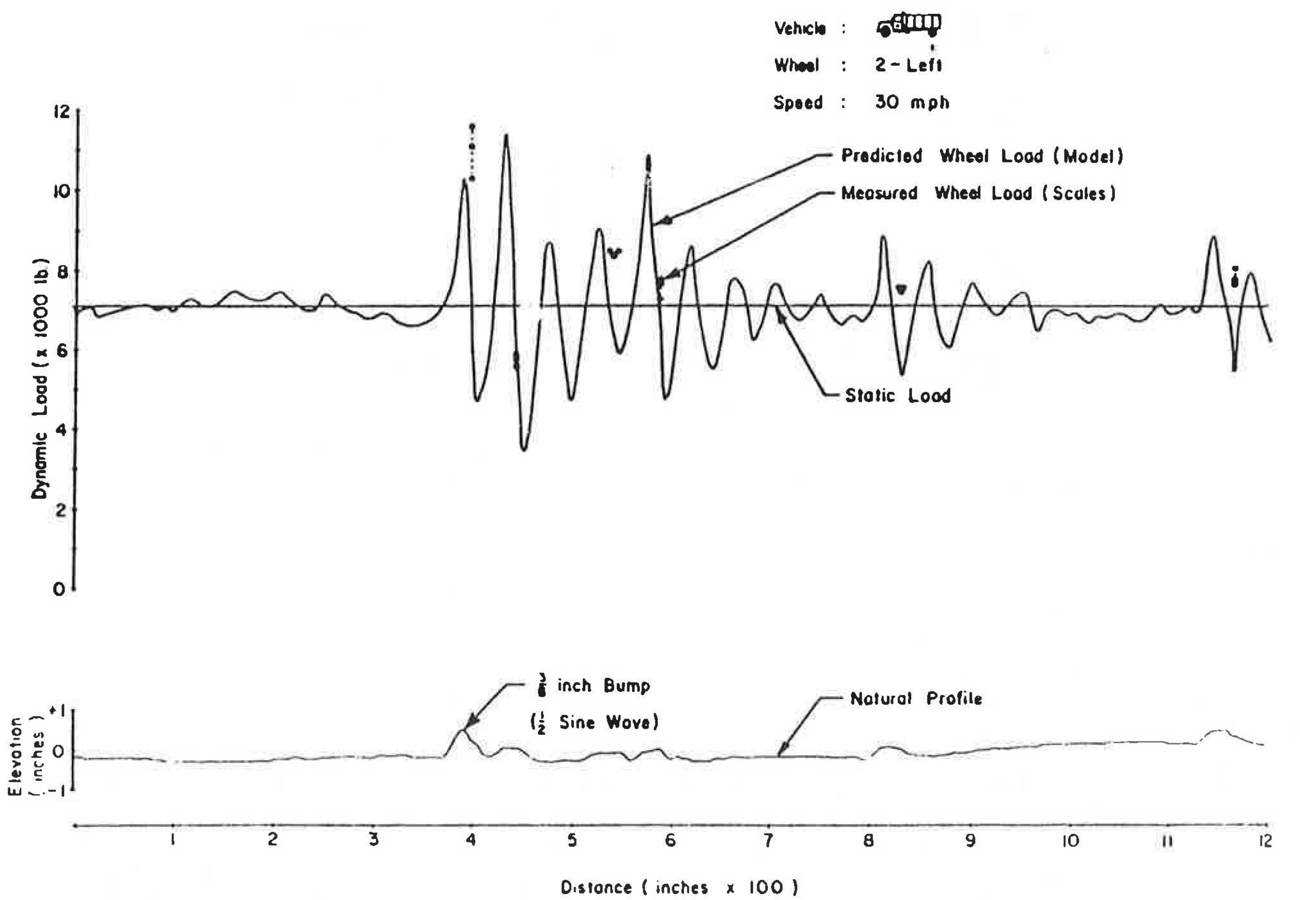


FIGURE 5 Comparison of measured and computed dynamic loads of a fully loaded truck moving at 30 mph (*4*).

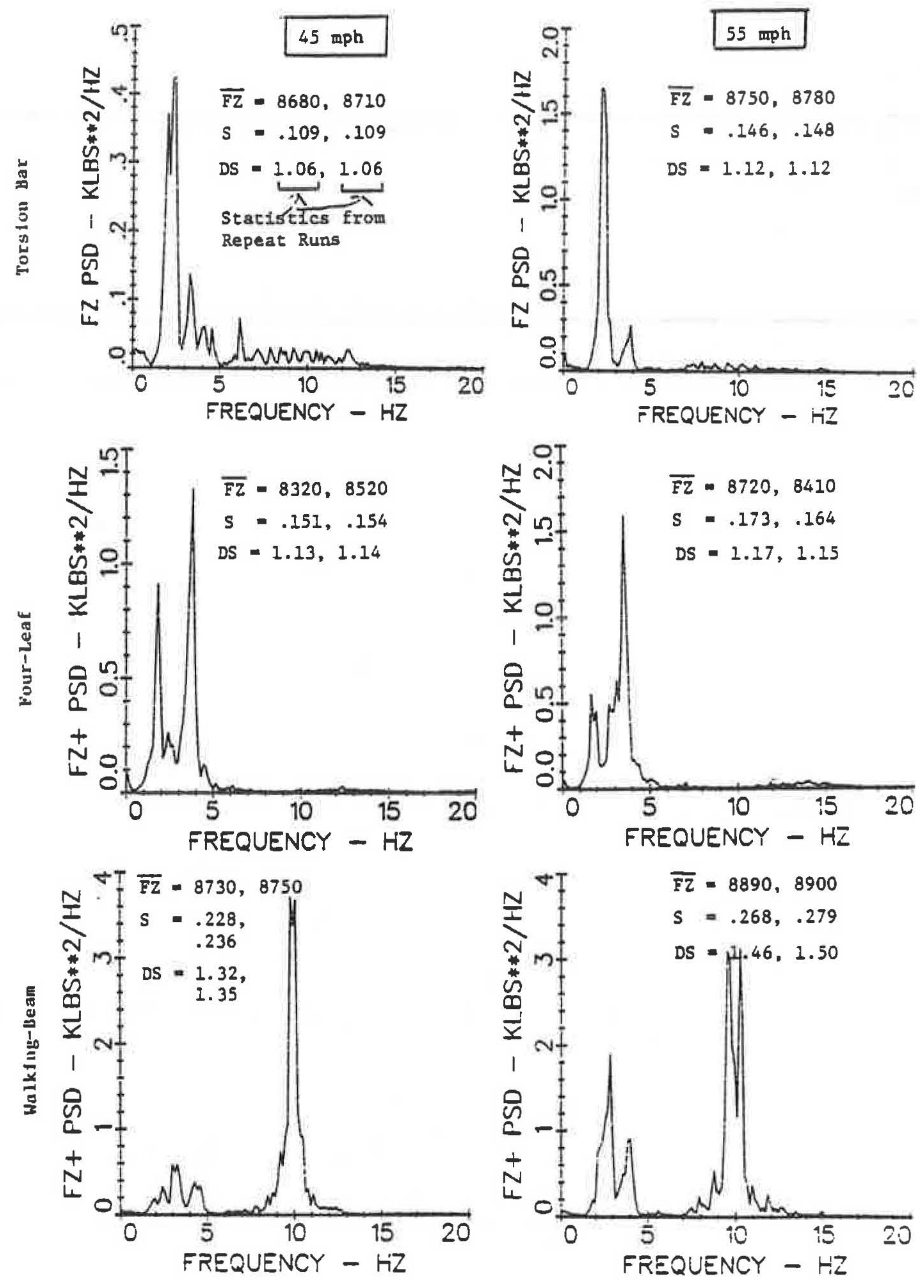


FIGURE 6 Response of vehicles, by suspension type and speed, on aged portland cement concrete roadway with considerable faulting, cracking, and patching (*5*).

Geometry

Complex geometry will inevitably lead to complicated computer programs which are expensive to run. This is especially true if the geometry is three-dimensional and the loading is dynamic. Significant simplifications can be achieved by imposing restrictions on the generality of the geometry and load distribution.

For pavement analyses, the single most effective restriction is that of allowing only semifinite horizontally layered models. This will effectively reduce the dimensionality of the problem from three to two dimensions, since with viscoelastic materials, the problem reduces to a superposition of similar axisymmetric solutions. Unfortunately, this restriction precludes the analysis of joint and edge problems. Nevertheless, in the interest of progress and economy, this restriction has been adapted for the solutions used herein.

SAPSI Program

A computer code was developed which takes advantage of the above-mentioned simplifications and involves many of the concepts embodied in the SASSI code (a computer program developed for the solution of soil-structure interaction problems). This new code, SAPSI, is a menu-driven program written in FORTRAN and can be utilized on an IBM-PC/AT (*7*).

SAPSI can be used to calculate the response of a viscoelastic

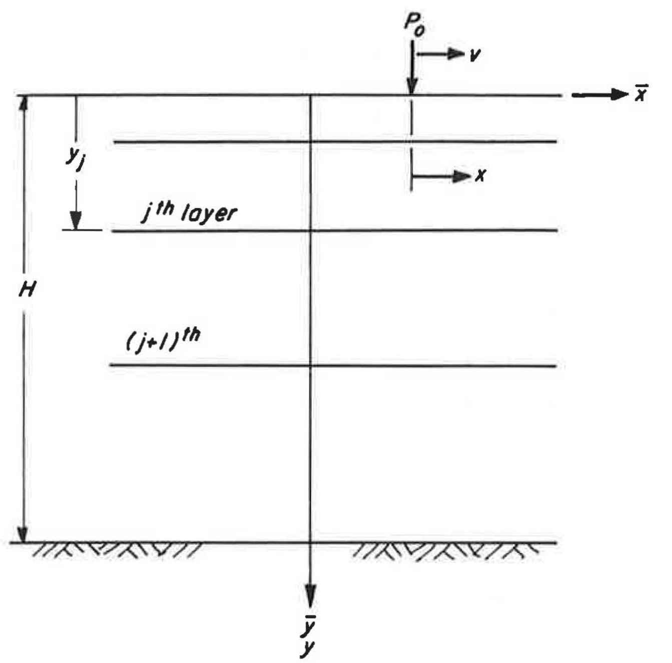


FIGURE 7 Model for pavement-subgrade system subjected to moving loads.

layered system subjected to surface circular loads. It can be assumed that the layered system is resting on a half space. This is simulated by vertically extended layers and by a series of dashpots attached to the bottom of the extended layers. The layer properties, which include the shear modulus, the damping ratio, and Poisson's ratio, can be varied with the excitation frequencies of the loads. Multiple loads (up to 40) are acceptable for harmonic and transient motions. The loads may have different radii and time histories. Static loads can be simulated by specifying a harmonic motion with zero excitation frequency.

The program uses special techniques in the frequency domain to interpolate results obtained at only a few frequencies (up to 20 frequencies can be analyzed). Thus, computation time can be significantly reduced. Furthermore, to facilitate modifications and adaptability to different computer memory sizes, the program also uses the dynamic allocation technique. This allows the dimensions of the program to be easily increased, if so desired, without much effort.

With respect to output for time histories, the program can calculate displacement, stress, or strain at any point in the middle of any layer (in global coordinates) up to 108 points. The output can be as follows:

- displacements at layer interfaces,
- stresses at center of layers,
- strains at center of layers.

The general output or the printout contains control information, input layer profile and properties, eigen values and vectors, and maximum responses for displacements, stresses, and strains.

LABORATORY EVALUATION OF DYNAMIC PROPERTIES OF PAVING MATERIALS

To determine the dynamic response of representative pavement materials, a testing system was devised which can test specimens as hollow cylinders at frequencies up to 30 Hz. The specimens can be subjected to axial, torsional, or combined axial and torsional loads in this frequency range to attempt to simulate the three-dimensional stress states that occur in pavement materials in situ when subjected to moving loads. This equipment has been described in detail by Sousa and Monismith (*9*).

Although they reported the results of tests on an asphalt concrete (California Type B mixture, ⅜-in. maximum size aggregate consisting of Watsonville granite, AR-4000 asphalt cement supplied by Chevron) and Vicksburg silty clay (LL

TABLE 1 COMPARISON OF MOVE PROGRAM AND STATIC SOLUTION (*8*) FOR HORIZONTAL AND VERTICAL DISPLACEMENTS IN MULTILAYERED SYSTEMS

Coordinate x (ft)	Horizontal Displacement 10^{-3} (ft)		Vertical Displacement 10^{-3} (ft)	
	MOVE	Poulos and Davis	MOVE	Poulos and Davis
3	0.07713	0.07716	0.6721	0.6425
6	0.05226	0.05296	0.3930	0.3802
12	0.00990	0.01024	0.1459	0.1423
18	-0.02689	-0.02367	-0.03586	-0.03539
24	-0.05051	-0.04734	-0.01404	-0.01391
30	-0.06255	-0.05852	-0.03281	-0.03293

TABLE 2 COMPARISON OF MOVE PROGRAM AND STATIC SOLUTION (*8*) FOR NORMAL AND SHEAR STRESSES IN MULTILAYERED SYSTEMS

Coordinates (x, y) ft.	Normal Stress σ_{yy}, psf		Shear Stress τ_{yy}, psf	
	MOVE	Poulos and Davis	MOVE	Poulos and Davis
(3, 6)	137.10	126.41	66.70	61.29
(3, 12)	95.50	97.30	18.40	21.40
(3, 18)	78.96	74.23	8.76	9.25
(3, 24)	62.26	61.96	5.26	5.14
(3, 30)	52.57	52.40	5.57	5.65
(6, 18)	63.44	63.45	15.62	15.39
(6, 24)	56.03	56.07	9.45	9.32
(6, 30)	48.54	48.62	10.72	10.53

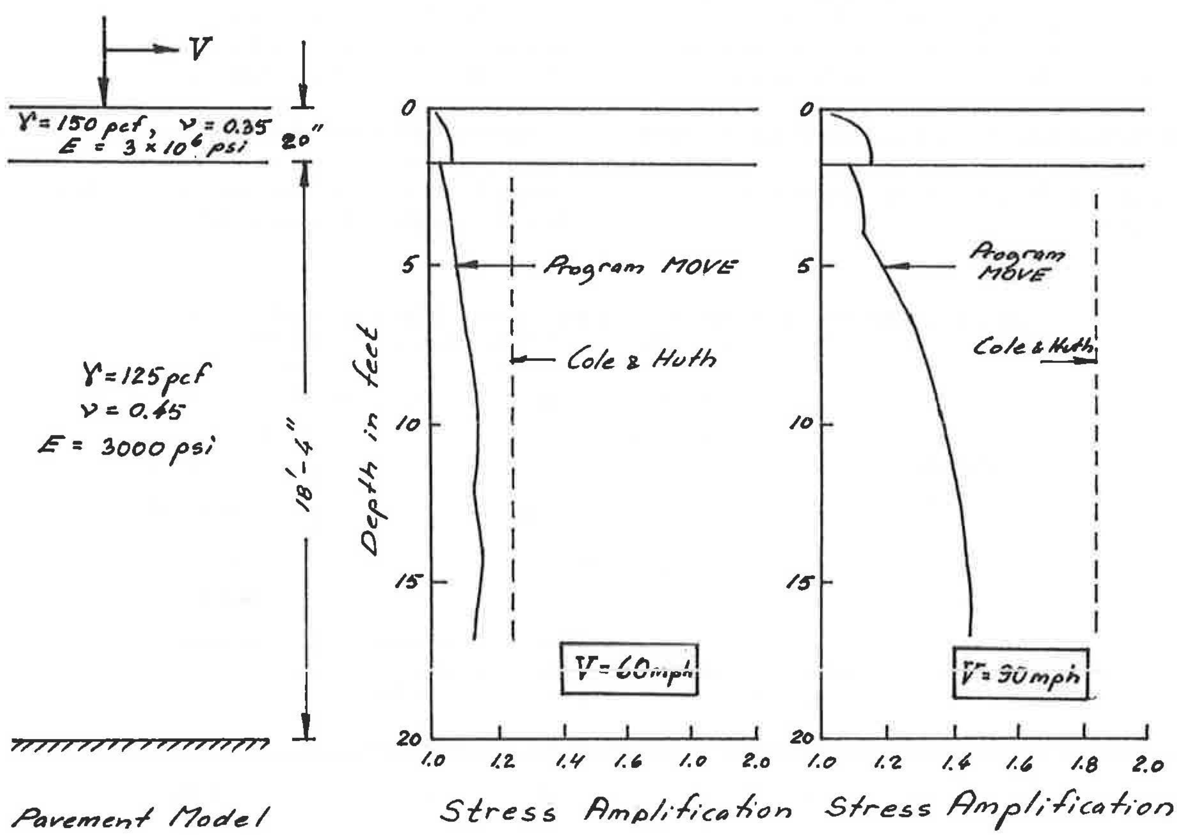


FIGURE 8 Load moving at 0, 60, and 90 mph on an asphalt concrete layer 20-in. thick resting on a half-space subgrade.

35, PI 13), some of the test data are presented herein since they are germane to the analyses described below. Both materials were tested as hollow cylindrical specimens 18-in. high, 9-in. outside diameter, and with a 1-in. wall thickness.

Asphalt Concrete

The properties of the asphalt concrete were measured by the application of several vertical and torsional sinusoidal loads to the hollow cylindrical specimens at three different temperatures (11°C, 25°C, and 40°C). At 11°C the vertical sinusoidal compression pressure had a mean value of 40 psi and an amplitude of 70 psi, and the torsional sinusoidal loads produced shear stresses with a mean value of 12 psi and amplitudes of 20 psi. At 25°C and 40°C, the axial values were 25 psi and 40 psi and shear stresses of 4 psi and 6 psi, respectively. At each temperature level the frequency of the sinusoidal loads varied between 0.5 and 20 Hz (0.5, 1.0, 5.0, 10, 15, and 20 Hz). A total of 200 loading cycles was applied at each frequency (at 0.5 Hz only 60 cycles were applied, and at 1.0 Hz only 100 cycles were applied). All tests were performed under stress control (feedback from the load cells) with LVDTs placed 2.5 in. from the ends of the specimen. Each specimen was initially tested at 11°C, then at 25°C, and at 40°C. This sequence was repeated three times. A specimen was maintained at each temperature level for at least 3 hr prior to testing. Vertical vibratory loads (20 to 0.5 Hz) were applied first, then torsional vibrations (20 to 0.5 Hz). This sequence was repeated twice at each temperature.

The effect of temperature and frequency on the variation of the dynamic modulus $|E^*|$ and the dynamic shear modulus $|G^*|$ is illustrated in Figure 9. Repeatability of the results after various tests had been performed indicates that the dynamic properties of the specimen are not influenced by previous testing frequencies and temperatures. Thus, several different tests can be performed on the same specimen using various frequencies, temperatures, load applications, and levels of stress without changing the data significantly. However, the stiffness moduli exhibit strong dependence on frequency and temperature.

From stress-strain hysteresis loops (Fig. 10), the internal damping can be determined. The effects of temperature and frequency on the values of internal damping, measured under vertical loading and torsional loading, are plotted in Figure 11. Note that the differences in damping increase with temperature. Temperature and frequency effects are particularly noticeable on the values of the dynamic Poisson's ratio $[\nu^* = E^*/(2\ G^*) - 1]$, as shown in Figure 12. The high values obtained at 40°C and at 25°C under low frequencies are probably due to volume change during the shear loading cycles. Under those conditions the contribution of the bitumen for the resistance of the mix is reduced, and this results in a behavior more like that of an aggregate. Similar results have been reported by Hills and Heukelom (*10*).

Silty Clay

Specimens of silty clay were tested at three strain levels (0.01, 0.1, and 1.0 percent), four frequency levels (0.5, 1.0, 5.0, and 10 Hz), and four levels of confining pressure (29, 20, 11, and again at 29 in. Hg). During testing, approximately 30 sinusoidal load cycles were applied at each level.

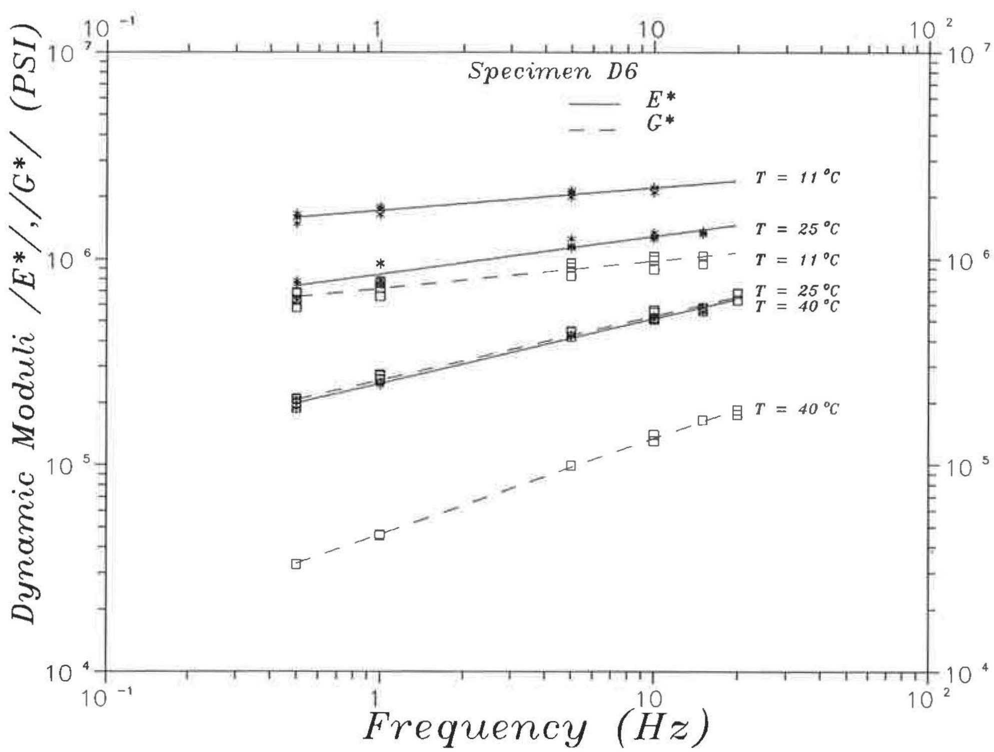


FIGURE 9 Influence of frequency and temperature on dynamic moduli of an asphalt concrete in compression and shear.

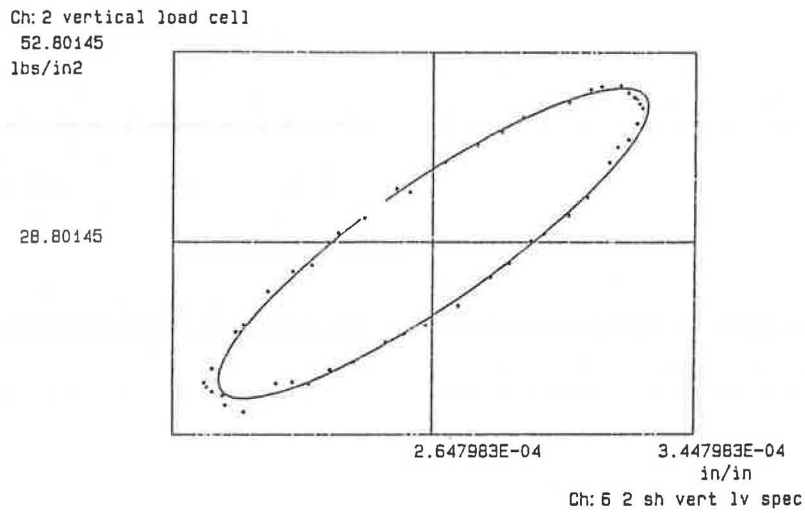


FIGURE 10 Hysteresis loop for an asphalt concrete mixture where frequency = 1 Hz, T = 40°C.

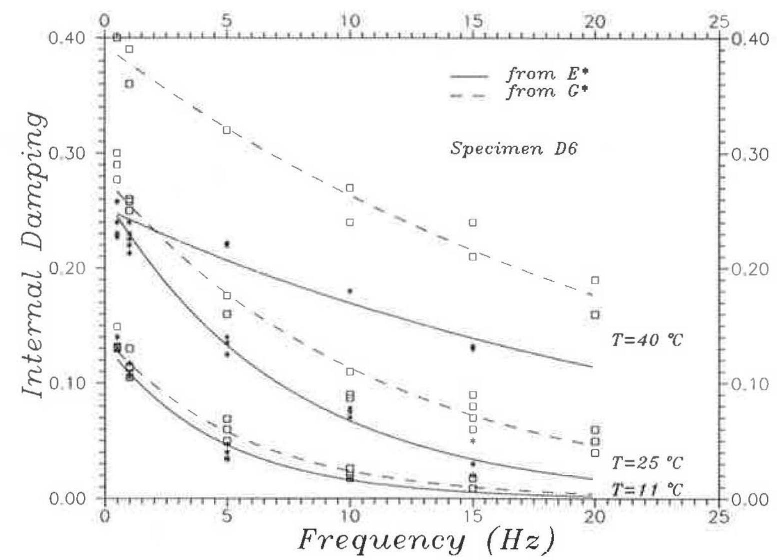


FIGURE 11 Influence of temperature and frequency on damping characteristics of an asphalt concrete.

Figure 13 illustrates the effects of shear strain amplitude and confining stress on the dynamic shear modulus $|G^*|$. To obtain these values, confining pressure was changed at each strain level; this was done to mitigate the effects of damage that might occur at higher strain levels on the test results. The repeatability of results at 29 in. Hg after several cycles were applied at 20 and 11 in. Hg indicates that the number of load applications (even if applied at lower confining pressures and different frequencies) does not significantly alter the dynamic shear modulus. Furthermore, it can be inferred from the data (Fig. 14) that frequency of loading does not affect the dynamic shear modulus.

The effects of confining stress, frequency, and strain amplitude on damping were also evaluated. The data presented in Figure 15 suggest that internal damping increases with increase in shear strain amplitude but is little affected by confining pressure. Furthermore, the effects of loading frequency on internal damping are also evident. Note also that the frequency effect is similar at each level since all of the lines plotted are essentially parallel.

ANALYSIS OF A PAVEMENT DESIGN

This section presents a methodology used to assess the relative damage caused by tandem axles with three different suspension systems: a torsion bar, a four-leaf spring, and a walking beam.

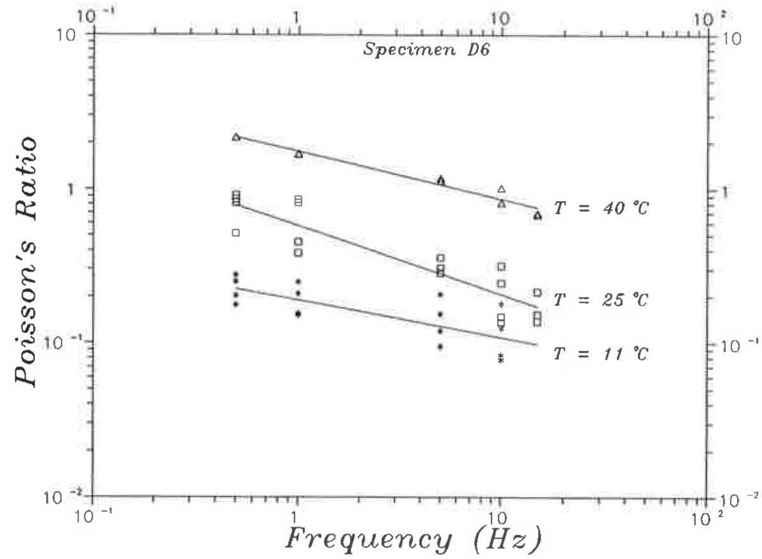


FIGURE 12 Influence of temperature and frequency on Poisson's ratio for an asphalt concrete.

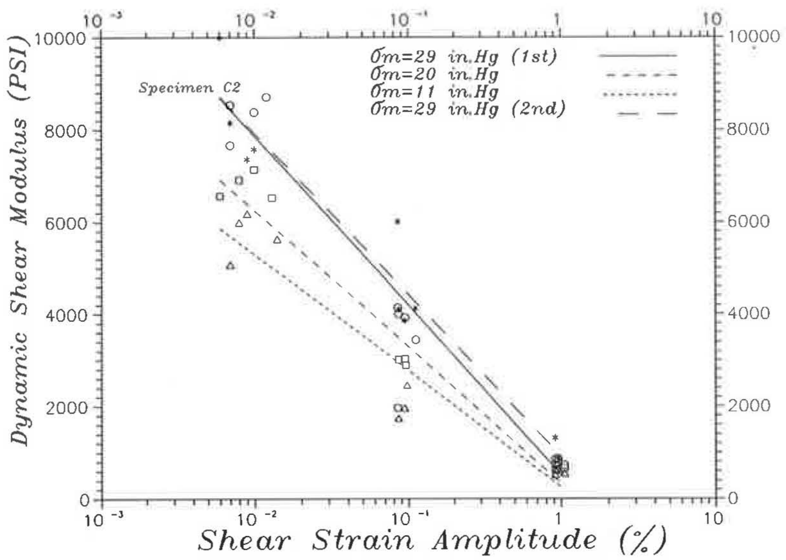


FIGURE 13 Influence of shear strain amplitude on the dynamic shear modulus of a silty clay specimen at three different confining pressures.

To properly solve this problem requires data defining the time histories of the loads applied to a pavement structure with trucks equally loaded but equipped with different suspension systems.

Gillespie et al. (*5*) have presented data from measurements of the time variations of loads applied to the same pavement section and nearly conforming to these requirements. Their data, illustrated in Figure 16, represent the loads measured at the wheel hub and do not include the inertia forces caused by vibrations of the mass of the wheel. This implies that the actual variation in magnitude of the dynamic loads on the pavement was only slightly higher than that recorded and that the data can therefore be considered representative.

Another requirement is to decide on the mode or modes of distress to be analyzed, that is, modes that will lead to a reduction in pavement serviceability. In the example that follows, the fatigue mode of distress was selected. The relative damage effects of the three types of suspensions were determined in three steps:

1. *Determination of time histories of the tensile strain at the bottom of a representative pavement structure using dynamic material properties determined in this investigation.* The strains were computed using the SAPSI program (*7*). This program, as noted above, simulates the dynamic response of layered systems to dynamic surface loads and incorporates the variation of the material properties with loading frequency.
2. *Determination of pavement life expectancy using gener-*

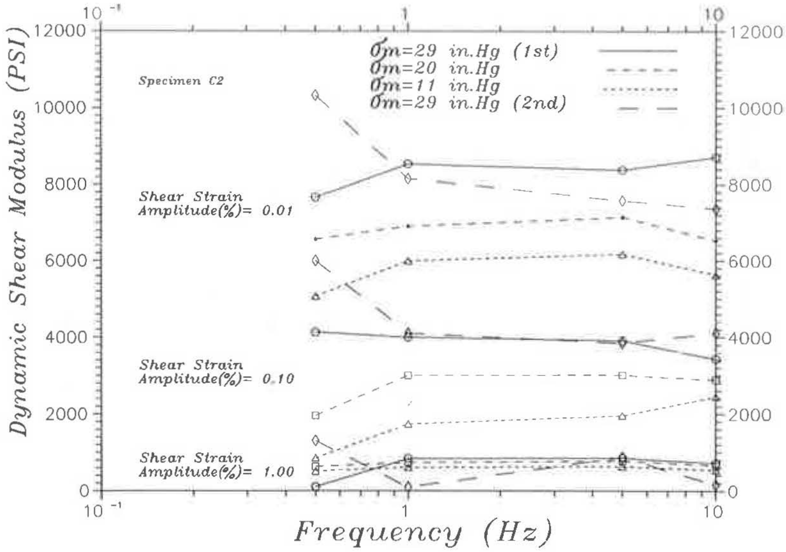


FIGURE 14 Influence of frequency loading on the dynamic shear modulus.

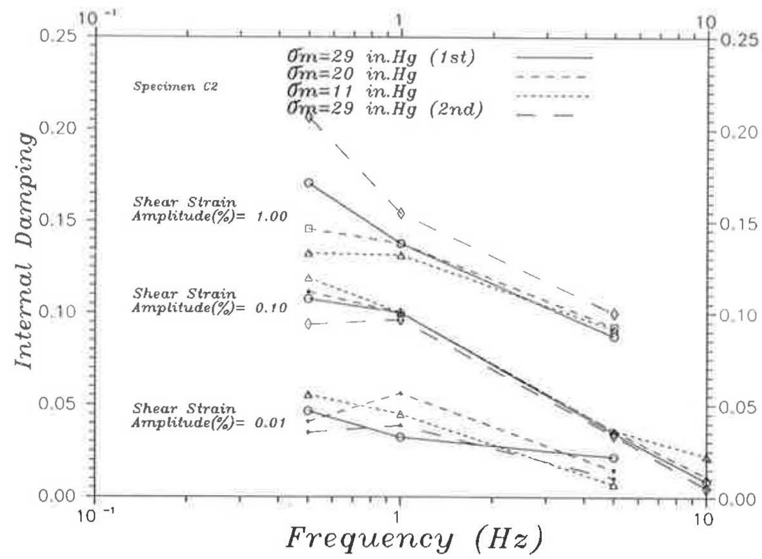


FIGURE 15 Influence of load frequency on internal damping at different strain levels for Vicksburg silty clay.

ally accepted fatigue criteria. For each of the suspension types the number of load applications to failure was computed. The Linear Summation of Cycle Ratio Cumulative Damage Hypothesis was used to assess the relative damage imposed at each level of strain.

3. *For comparison, a reduction of pavement life (RPL) index was developed for each suspension type.* Each RPL value represents the percentage of pavement life consumed solely by the dynamic effects incurred by one type of suspension. The definition of the RPL index is as follows:

$$\text{RPL} = 1 - N_F(\text{suspension})/N_F(\text{static}) \qquad (2)$$

where

N_F (static) = number of load applications to failure computed by current quasi-static methods.

N_F (suspension) = number of load repetitions to failure (taking into consideration the dynamic effects of the suspension).

During this analysis it was assumed that the dynamic loads produced by a moving truck on a rough surface were a random phenomenon. Consequently, any particular point on the pavement may be subjected to the full spectrum of loads that a given truck might apply. In essence, any single point in the wheel path is likely to sustain the same level of loading as any other point might sustain. In addition, based on the analysis presented earlier, velocity effects of a moving load (velocity > 0) on a layered structure are negligible for velocities below 70 mph.

These two considerations enable the conversion of the spatial and temporal problem of determining the maximum strain variation under a moving truck to that of determining the

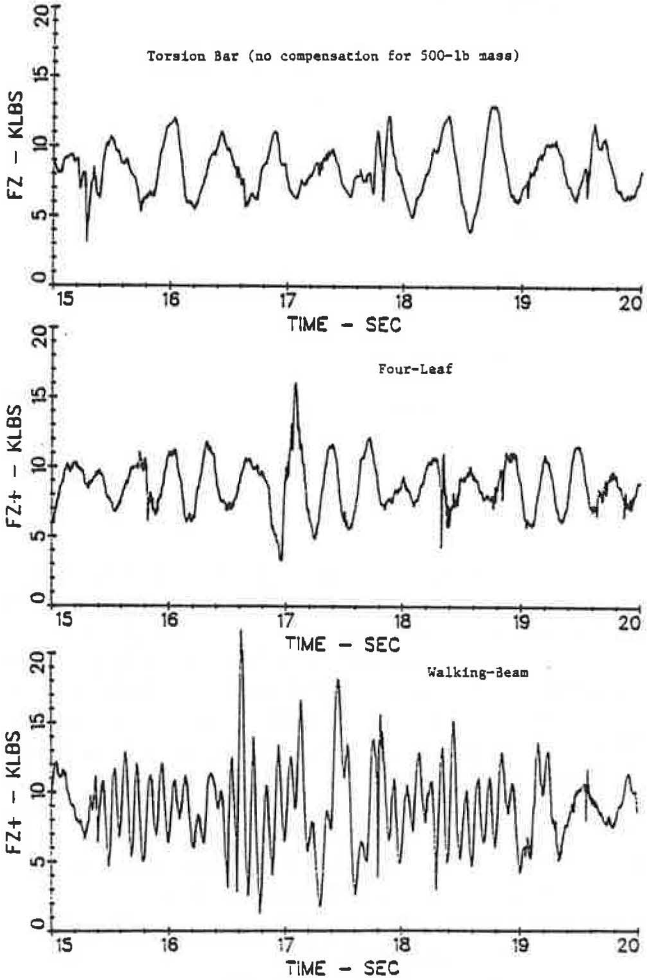


FIGURE 16 Comparison of three vehicle responses to the same road input, by type of suspension (note that signals are not accurately synchronized) (*5*).

time history of the tensile strain (at any chosen point on the pavement structure) for a nonmoving (velocity = 0) randomly applied load. According to this assumption, one can state (for instance) that 4.8 sec of time strain history (for a single point on the layered structure) under a nonmoving random load represents the maximum variation of the strain (on equivalent points of the layered system) over a section of pavement 0.073 mile long excited by the same load (or truck) moving at 55 mph [0.073 mile = 4.8 (sec) 55 (mph)/3,600 (sec/hr).]

Figure 17 illustrates this assumption. The solid line represents the time variation of the tensile strain at the bottom of the asphalt concrete layer. The two peaks are due to the passage of a moving (velocity = 55 mph) tandem wheel suspension (the difference in the values is due to the time variation of the loads on each of the wheels). The dashed line represents the time variation of the tensile strain for the nonmoving (velocity = 0) case but subjected to the same time load history.

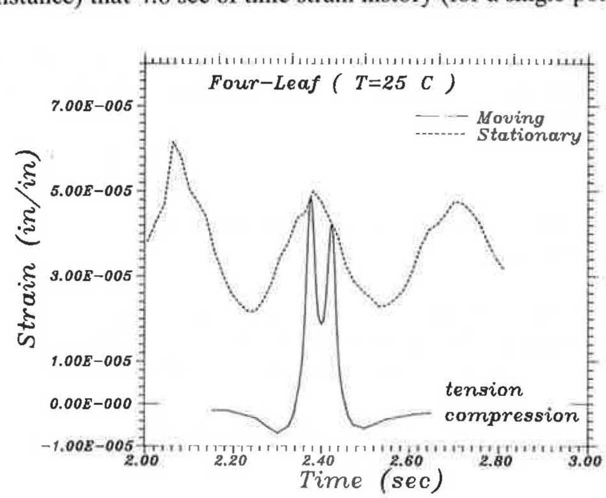


FIGURE 17 Time variation of tensile strain at a point on the underside of the asphalt concrete layer.

Pavement Life Determination for Quasi-Static Case

To determine the pavement life for the quasi-static or constant-load case (i.e., no dynamic load variation with time), the pavement system was assumed to respond to the load as a layered elastic system. For an asphalt concrete pavement system, the stiffness modulus of the asphalt-bound layer is dependent on the velocity of the moving vehicle (time of loading) and the temperature of the material at the time of loading. In this type of analysis, equally loaded trucks equipped with different suspension types and traveling at the same speed are expected to produce the same pavement response and, hence, the same damage.

To determine the time of loading to be used to estimate the stiffness modulus of the asphalt-bound layer, use can be made of an approach recommended by McLean (*11*) and shown in Figure 18. In this figure the solid curves are those computed by McLean assuming square vertical compressive stress pulses; as shown in the figure, the time of loading depends on the layer thickness as well as the velocity of the vehicle. As an example, this figure suggests that asphalt properties obtained from a testing sequence using square waves with a loading time of 0.024 sec are representative of the asphalt concrete behavior in a 10-in.-thick pavement structure excited by a truck traveling at 30 mph. Barksdale's (*12*) analysis for

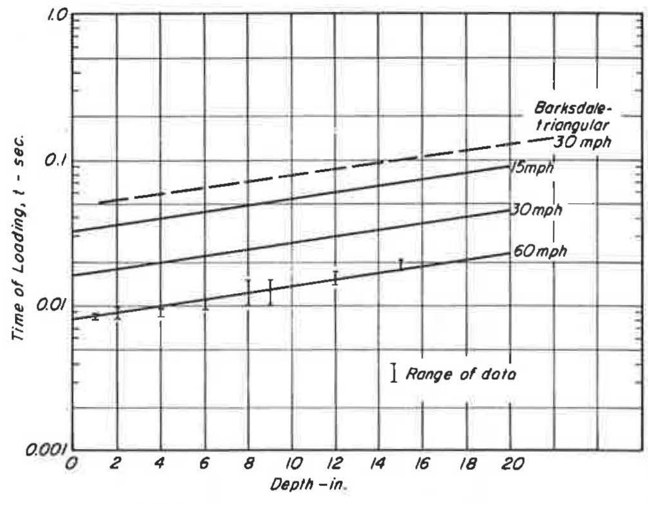


FIGURE 18 Relationship between equivalent time of loading and depth for vertical compressive stress (*11*).

TABLE 3 STIFFNESS CHARACTERISTICS OF ASPHALT CONCRETE FOR QUASI-STATIC ANALYSIS

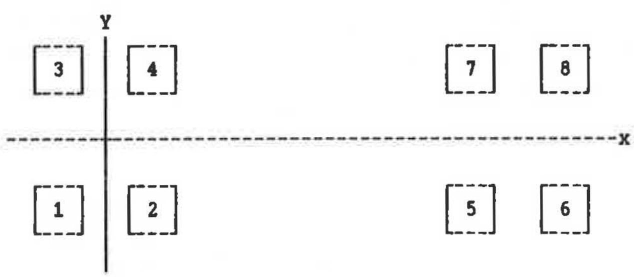
Temperature °C	Shear Modulus[1] $\|G^*\|$ psi	Poisson's[2] Ratio ν	S_{mix}[3] $\|E^*\|$ psi
25	4.24×10^5	0.28	1.09×10^6
11	8.92×10^5	0.13	2.01×10^6

1. From line of best fit, Fig. 20, assuming 5 Hz loading frequency.
2. From line of best fit, Fig. 22, assuming 5 Hz loading frequency.
3. Computed from $|E^*| = |G^*|/2(1 + \nu)$.

the same conditions (also shown in Figure 18) suggested a testing sequence based on triangular pulses with loading times of 0.075 sec. If sinusoidal loading is chosen instead of triangular or square loading waves, it is reasonable to expect (from interpolation) that a loading time of 0.03 sec would be representative of a truck traveling at 55 mph on the same 10-in.-thick pavement (Figure 18). In this analysis it was assumed that this loading time corresponds to asphalt concrete properties tested under a 5-Hz sinusoidal loading frequency [5 Hz = $1/(2\pi \times 0.03$ sec)].

For these loading frequencies, estimates of the stiffness properties of the asphalt concrete to be used for the quasi-static analyses are shown in Table 3.

Figure 19 illustrates the dimensions of the tandem axle used in the analysis. A 5,000-lb static load was applied to each circular surface location with a radius of 4.2 in. (tire pressure = 90 psi). The pavement system consisted of 12 in. of asphalt concrete resting on the silty clay subgrade.



LOAD NUMBER	X COORDINATE (FEET)	Y COORDINATE (FEET)
1	-0.5265	2.0
2	0.5265	2.0
3	-0.5265	-2.0
4	0.5265	-2.0
5	6.465	2.0
6	7.526	2.0
7	6.465	-2.0
8	7.526	-2.0

FIGURE 19 Spatial distribution of tandem-axle loads.

The maximum tensile strain at the bottom of the asphalt layers was computed by the SAPSI program. This program is also capable of performing static analyses. However, for increased accuracy, the subdivision of each layer into idealized sublayers of the same material is necessary. Table 4 shows the thicknesses of the various layers used in the calculation. However, the program can only compute the stresses, strains, or displacements at the center of each layer. Thus, to determine the tensile strains of an element at a distance sufficiently close to the bottom of the asphalt concrete layer, an idealized thin sublayer had to be created. The stresses were computed 0.06 in. from the bottom of the asphalt layer.

Estimates of the fatigue life were made using the relationship for asphalt concrete developed by Finn et al. (*13*) for less than 10 percent cracking in the wheel path:

$$\log N_F = 15.947 - 3.291 \log (\varepsilon_t/10^{-6}) - 0.854 \log (S_{mix}/10^3) \quad (3)$$

where

N_F = number of load repetitions to failure,
ε_t = tensile strain in asphalt layer (in./in.), and
S_{mix} = asphalt mixture stiffness modulus (dynamic modulus in psi).

For the two temperatures the computed strains and the corresponding fatigue lives according to Equation 3 are shown in Table 5.

Dynamic Load Considerations in Pavement Life Determination

To establish the influence of the load applied dynamically, as compared to the previous solution for the quasi-static case, at least three major aspects must be considered:

1. time variation of the load applied to the pavement,
2. pavement model capable of simulating dynamic response, and
3. variation of material properties as a result of different loading frequencies.

TABLE 4 IDEALIZATION OF PAVEMENT SYSTEM FOR STRAIN DETERMINATION

Layer Number	Thickness (in.)	Material
1	6.00	
2	4.80	
3	2.40	Asphalt
4	1.20	Concrete
5	0.48	
6	0.12	
7	0.48	
8	1.20	
9	2.40	Subgrade
10	4.80	(silty clay)
11	12.00	
12	36.00	
13	60.00	
14	84.00	
15	120.00	

The spatial loading pattern for the dynamic loads was the same as for the quasi-static solution (Fig. 19). The time history for each suspension type (Fig. 16), was applied simultaneously to each of the eight load locations.

The SAPSI program is capable of simulating the dynamic response of layered structures excited by loads on the surface. The layered structure is assumed to consist of a number of layers over a half space. Viscoelastic materials are assumed in both the layers and the half space. To simulate the half space, the program automatically generates 10 additional layers with thicknesses varying depending on the frequency of excitation. Table 6 lists the thicknesses of the sublayers used to simulate the pavement structure.

The program is capable of incorporating frequency-dependent material properties. Careful consideration of the properties was necessary in order that the speed effect of the moving trucks might also be included. The current design criteria, used to convert velocity of moving trucks into appropriate loading frequencies for determination of material properties, has been described previously. Such criteria assume that the response of a pavement, $R(t)$, can generally be given by:

$$R(t) = LA_1e^{i(\omega_1)t} \tag{4}$$

where

t = time,
L = constant load applied by the truck,
A_1 = function of pavement structure, and
ω_1 = constant (function of the pavement structure and velocity).

With the incorporation of dynamic loads, L is no longer a constant. Furthermore, the variation of the rate of loading affects frequency-dependent material properties. Therefore, the combined effect of truck speed and the variation of the rate of loading must be incorporated into the model. If L is a function of time, it can be assumed that:

$$L(t) = S + De^{i(\omega_2)t} \tag{5}$$

where

S = static component of the load,
$De^{i(\omega_2)t}$ = dynamic component of the load, and
ω_2 = predominant frequency of the dynamic load.

Therefore, a dynamic analysis must consider a pavement response function, $R_D(t)$, such that:

$$R_D(t) = [S + De^{i(\omega_2)t}]A_2e^{i(\omega_1)t} \tag{6}$$

TABLE 5 FATIGUE LIFE CRITERIA FOR STATIC ANALYSIS

	Temperature, ^{o}C	
	25	11
Strain, ε_t in. per in. × 10^{-6}	35.2	24.2
Predominant Frequency	V = 55 mph (5 Hz)	
S_{mix} psi × 10^{6}	1.09	1.17
N_F[1]	183 × 10^{6}	373 × 10^{6}

[1] $\log N_F = 15.947 - 3.291 \times \log \left(\frac{\varepsilon_t}{10^{-6}}\right) - 0.854 \times \log \left(\frac{S_{mix}}{10^{-3}}\right)$

TABLE 6 PAVEMENT SYSTEM FOR DYNAMIC ANALYSIS

Pavement Structure

Layer Number	Thickness (in.)	Material
1	6.00	
2	4.80	
3	2.40	Asphalt
4	1.20	Concrete
5	0.48	
6	0.12	
7	0.48	Subgrade
8	1.20	(silty clay)
9	2.40	
10	4.80	

10 additional layers simulate half space

or

$$R_D(t) = A_2Se^{i(\omega_1)t} + A_2De^{i[(\omega_1) + (\omega_2)]t}$$

where

A_2 = constant dependent of pavement structure.

Essentially, this indicates that the dynamic response to a moving truck can be given by the sum of the following two components:

$$A_2Se^{i(\omega_1)t}$$

which represents the effect of the static component of the load and can be determined by current quasi-static analyses with material properties depending only on truck speed and pavement structures; and

$$A_2De^{i[(\omega_1) + (\omega_2)]t}$$

which represents the response of the pavement due to dynamic effects. The material properties used in this analysis should be determined at a frequency level $(\omega_L) = (\omega_1) + (\omega_2)$.

To determine the actual material properties of the pavement, taking into account the dynamic components of pavement response, a frequency shift (ω_1 = 5 Hz) is necessary to simulate the adopted truck speed of 55 mph. To accomplish this, material properties at each frequency level were replaced by those obtained at a frequency level 5 Hz higher (see Figures 20, 21, and 22). The resulting properties are summarized in Tables 7, 8, and 9. Material properties at intermediate frequencies can be interpolated within the program.

Time histories of the tensile strain obtained with these properties using SAPSI are plotted in Figures 23, 24, and 25. The general shape of each of these time histories is similar to that of the corresponding load (see Figure 16).

SAPSI is capable of determining the time variation of the strain, at any particular point, caused by a moving load (assuming no velocity effects as discussed earlier). The output of such calculations obtained with the four-leaf suspension traveling at 55 mph at the bottom of the asphalt concrete layer (X = 0, Y = 2 ft) is shown in Figure 26. Note the difference in the high of the two peaks due to the time variation of the loads. The first peak is caused by the passage of loads 1 and 2 (see Figure 19) and the second due to loads 3 and 4. Figure 27 shows, on a different time scale, the same graph superimposed on the time variation of the maximum tensile strain obtained with the four-leaf suspension (Fig. 24). The graph in Figure 17 is an enlargement of this plot in the time span 2 to 3 sec.

To determine the fatigue life of the pavement, assuming it is subjected to only one type of suspension loading, the Linear Summation of Cycle Ratios Cumulative Damage Hypothesis was used. The time history of the tensile strain caused by each type of suspension was digitized into 256 equal parts. For each part (i), the fatigue life (N_i) corresponding to that level of strain was computed using the fatigue criteria shown in Equa-

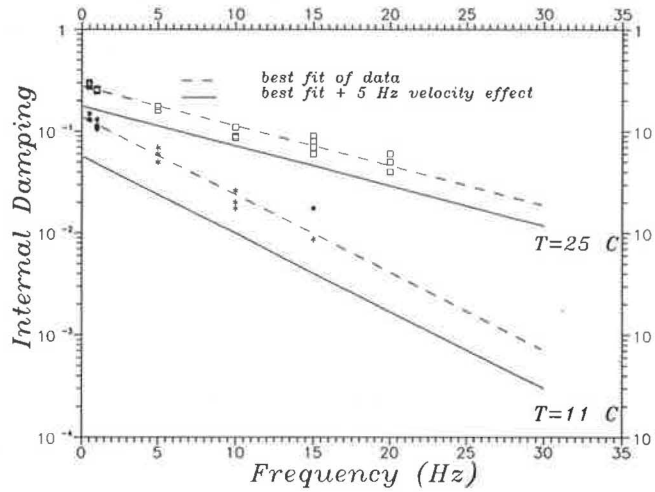


FIGURE 21 Variation of internal damping with frequency for an asphalt concrete mixture at 11°C and at 25°C; adopted properties simulate a 5-Hz velocity effect.

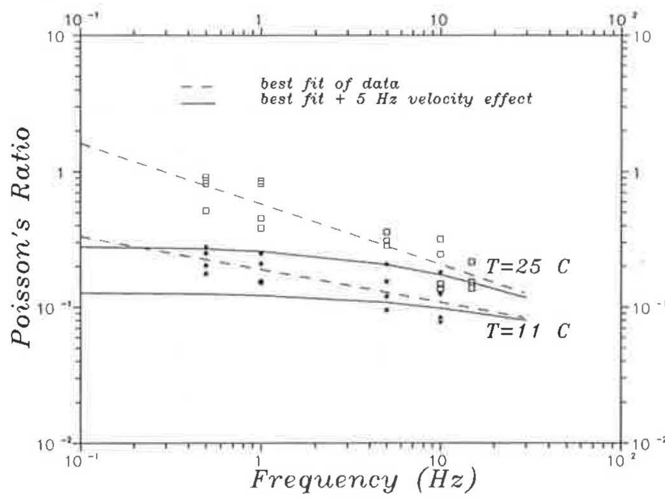


FIGURE 22 Variation of Poisson's ratio with frequency for an asphalt concrete mixture at 11°C and at 25°C; adopted properties simulate a 5-Hz velocity effect.

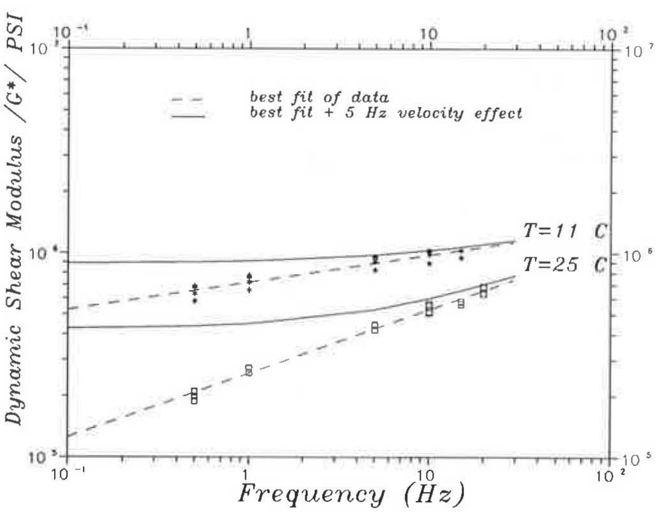


FIGURE 20 Variation of dynamic shear modulus with frequency for an asphalt concrete mixture at 11°C and 25°C; adopted properties simulate a 5-Hz velocity effect.

TABLE 7 MATERIAL PROPERTIES FOR ASPHALT CONCRETE CONSIDERING 5-Hz FREQUENCY SHIFT TO SIMULATE TRUCK VELOCITY AT 11°C

Frequency (Hz)	Adjusted Frequency	Shear Moduli |G*| (psi)	Internal Damping	Poisson's Ratio
0.1	(5.1)	892000	.056	0.127
0.5	(5.5)	901000	.053	0.125
1.0	(6.0)	911000	.048	0.122
5.0	(10.0)	976000	.024	0.108
10.0	(15.0)	1030000	.010	0.098
15.0	(20.0)	1071000	.004	0.091
30.0	(35.0)	1154000	.0003	0.080

TABLE 8 MATERIAL PROPERTIES FOR ASPHALT CONCRETE CONSIDERING 5-Hz FREQUENCY SHIFT TO SIMULATE TRUCK VELOCITY AT 25°C

Frequency (Hz)	Adjusted Frequency	Shear Moduli |G*| (psi)	Internal Damping	Poisson's Ratio
0.1	(5.1)	427000	.1761	0.278
0.5	(5.5)	437000	.1698	0.269
1.0	(6.0)	449000	.1623	0.258
5.0	(10.0)	527000	.1132	0.206
10.0	(15.0)	598000	.0721	0.172
15.0	(20.0)	654000	.0459	0.151
30.0	(35.0)	778000	.0118	0.117

TABLE 9 MATERIAL PROPERTIES OF SUBGRADE (SILTY CLAY)

Frequency (Hz)	Shear Moduli |G*| (psi)	Internal Damping	Poisson's Ratio
0.1	3,000	0.06	0.30
0.5	3,000	0.05	0.30
1.0	3,000	0.04	0.30
5.0	3,000	0.02	0.30
10.0	3,000	0.01	0.30
15.0	3,000	0.005	0.30
30.0	3,000	0.002	0.30

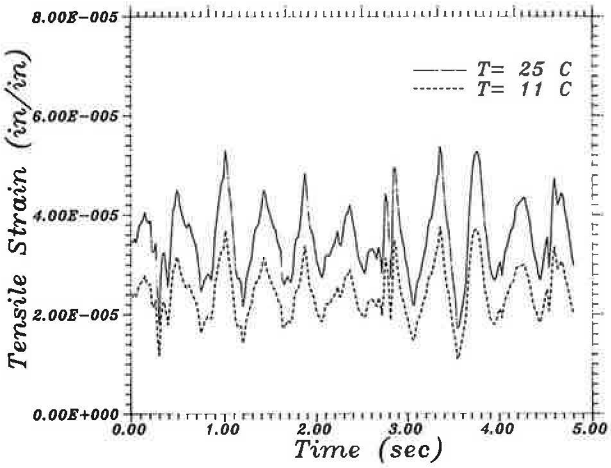


FIGURE 23 Time variation of tensile strain for torsion-bar suspension at 11°C and 25°C.

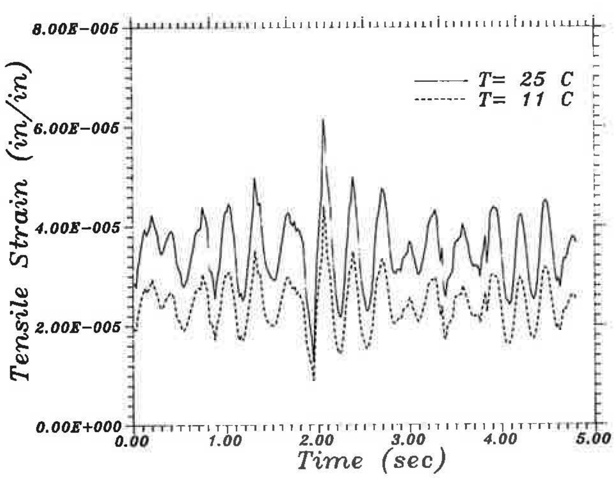


FIGURE 24 Time variation of tensile strain for four-leaf spring suspension at 11°C and 25°C.

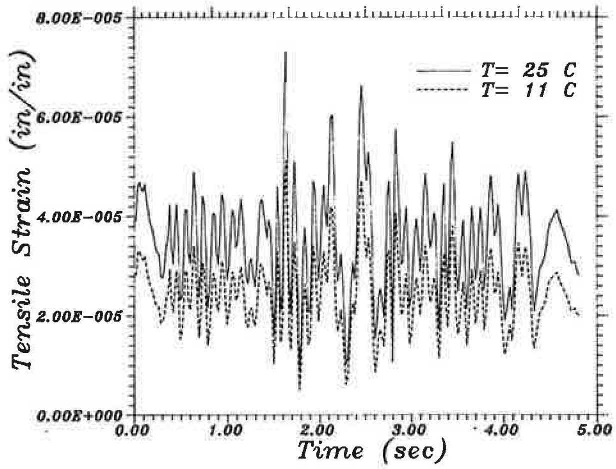


FIGURE 25 Time variation of tensile strain for walking-beam suspension at 11°C and 25°C.

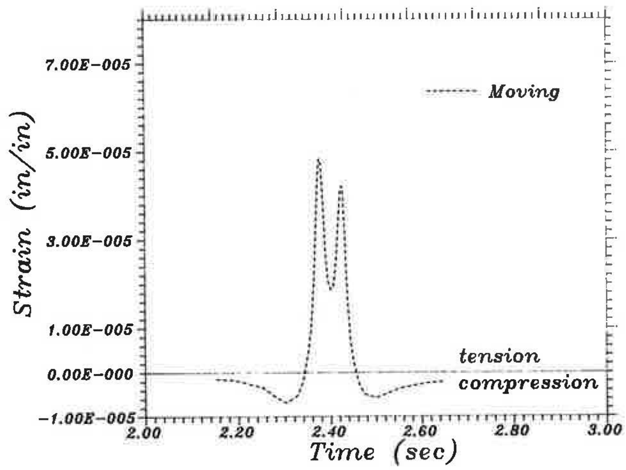


FIGURE 26 Time variation of tensile strain for four-leaf spring suspension with tandem configuration of Figure 19 at 25°C.

tion 3. The total number of load applications to failure for each suspension type was then calculated by:

$$1/N_F\ (\text{suspension}) = \sum_{i=1}^{256} [1/(256 \cdot N_i)] \qquad (7)$$

This analysis required consideration of the variation of the stiffness modulus of the mix with the predominant loading frequency of the suspension (see Figure 7) and the 5-Hz frequency shift. For the torsion bar, this value is 2 Hz; for the four-leaf, it is approximately 4 Hz; and for the walking beam, it is about 8 Hz. Tables 10 and 11 summarize the results.

The N_F values for each of the suspension types differ significantly from the values predicted by the quasi-static model. The lowest N_F value was obtained from the truck equipped with a walking-beam suspension ($N_F = 115E + 06$). If this value is compared with that predicted by the quasi-static model ($N_F = 183E + 06$), it can be inferred that the dynamic effects

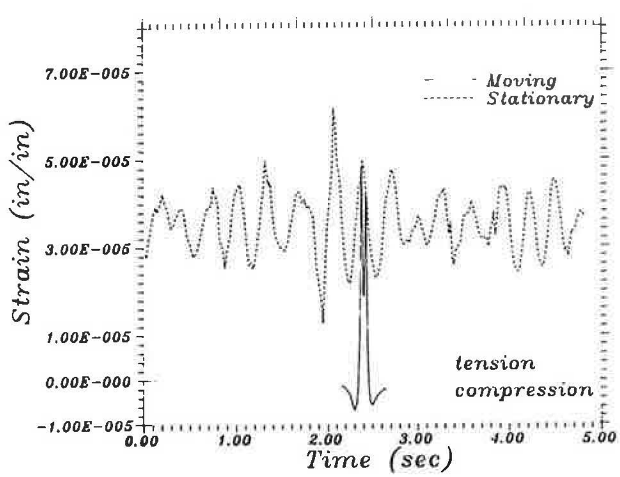


FIGURE 27 Time variation of tensile strain for four-leaf spring suspension with tandem configuration at 25°C superimposed on time variation of maximum tensile strain obtained with four-leaf suspension.

TABLE 10 ESTIMATED FATIGUE LIFE FOR THREE SUSPENSION TYPES AT 25°C

Temperature 25^oC	Loading/Suspension Type			
	Q/Static	Torsion	Four Leaf	Walking
Strain (ε_t) (E-04)	.352	See Fig. 23	See Fig. 24	See Fig. 25
Predominant Frequency	V = 55 mph (5 Hz)	5 + 2 = 7 Hz	5 + 4 = 9 Hz	5 + 8 = 13 Hz
S_{mix} psi (E + 06)	1.087	1.171	1.240	1.353
N_F * (E + 06)	183	148	143	115
RPL Percent	0	19	22	37

TABLE 11 ESTIMATED FATIGUE LIFE FOR THREE SUSPENSION TYPES AT 11°C

Temperature 11^oC	Loading/Suspension Type			
	Q/Static	Torsion	Four Leaf	Walking
Strain (ε_t) (E-04)	.242	See Fig. 23	See Fig. 24	See Fig. 25
Predominant Frequency	V = 55 mph (5 Hz)	5 + 2 = 7 Hz	5 + 4 = 9 Hz	5 + 8 = 13 Hz
S_{mix} psi (E + 06)	2.008	2.081	2.139	2.228
N_F * (E + 06)	373	306	304	252
RPL Percent	0	18	19	33

produced by walking-beam suspensions consume more than one-third of the expected pavement life.

The introduction of the RPL index facilitates the evaluation of the dynamic effects caused by different suspension types. An ideal suspension would have RPL = 0. Values for the torsion bar (RPL = 19) and for the four-leaf suspension (RPL = 22) at 25°C are quite close. This indicates that both suspension types produce similar levels of damage. However, the walking-beam suspension with an RPL of 37 is clearly the most damaging.

The RPL of a suspension depends on the roughness level of the pavement surface. The results obtained in this research are representative of a rough pavement surface; smaller RPL values may be expected for smoother pavements.

SUMMARY

A methodology has been developed to determine the effects of dynamic vehicle loads on pavements. It involves use of the SAPSI computer program, which can be used on an IBM-PC/AT. To estimate the influence of dynamic loads requires a knowledge of the load time history at a point in the pavement. If this is not available, it is possible to prepare an estimate provided the pavement profile and the dynamic response characteristics of representative trucks using the pavement are available.

In addition, a knowledge of the dynamic response of paving materials is required. For the SAPSI program, this requires a measure of the elastic and damping characteristics of the materials. For this investigation these properties were determined using the dynamic loading system described by Sousa and Monismith (*9*). The ability to control the values of three principal axes of stress or strain over a representative range of frequencies provides a valuable tool for determining material properties.

Results of the test program for the asphalt concrete illustrate the dependence of the stiffness and damping characteristics of the mixture on frequency, temperature, and mode of loading. Some nonlinearities are apparent in the response characteristics of this asphalt concrete. This is evidenced, for example, by changes in values for internal damping computed from the stiffness moduli $|E^*|$ and $|G^*|$. As the differences in damping determined in the axial and shear modes of loading increase, computed Poisson's ratios exceed 0.5, indicating some volume increase—most likely in the shear mode of loading.

This investigation also considered the effect of frequency, confining pressure, and strain level on the dynamic shear modulus and the internal damping characteristics of a silty clay. The data clearly indicate that frequency has no influence on the dynamic shear modulus of clay specimens (within the range tested). At the same time, frequency has a marked effect on the internal damping.

A representative pavement system consisting of an asphalt concrete layer resting directly on silty clay subgrade was analyzed by the SAPSI program to determine the pavement life that might result using actual load histories for three tandem-axle suspensions (on the same pavement traveling at the same speed) as compared to that obtained for the same axle with a uniform static load.

Results of the dynamic analysis suggest, at least for the load histories used herein, that pavement life is reduced when considering dynamic effects and that the magnitude of reduction is dependent on the tandem suspension. For this investigation, the largest reduction in pavement life was obtained for the axle with the walking-beam suspension. Comparable smaller reductions, as compared to the static case, were also obtained for the torsion-bar and four-leaf spring suspensions.

These determinations were based on load histories obtained from measurements of truck response on rough pavements. Less damage would result from operations on smoother pavements. Nevertheless, the study indicates that different damage will result from different suspension types for the same total static load. It would seem important to pursue this issue with further research since the RTAC study (*14, 15*) indicates similar findings. The trailer suspension producing the highest dynamic loading in the RTAC study was the walking beam, the same as obtained in this investigation.

The natural frequencies of the truck-suspension assembly play an important role on the amplitude of the dynamic components of the loads. As the predominant frequencies of the excitation caused by the pavement roughness approach the natural frequencies of the truck-suspension assembly, higher dynamic load components will occur.

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