Heavily Loaded Trailers: An Approach to Evaluate Their Interaction with Asphalt Concrete Pavements

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The Permits Department of the California Department of Transportation is often asked to issue permits for the movement of unusual vehicle configurations. It then becomes necessary to evaluate the damage these configurations cause. The shaking table of the Earthquake Engineering Research Center at the Richmond Field Station was used to investigate and compare some aspects of the dynamic behavior of a new super-heavy haul vehicle trailer (JXS), equipped with an hydraulic cylinder-nitrogen suspension, with those of four other, currently used, semitrailer types. Based on the data obtained during the tests conducted on the shaking table improvements on the JXS suspension were made, and it can be concluded that levels of the dynamic component of the loads, induced by the JXS at normal highway operations, are within the same range of magnitude as those produced by the other trailers studied. The results also suggest that the difference in performance between trailers equipped with leaf-spring suspensions and trailers equipped with air bag suspensions is greater than the difference between tridem trailers and tandem trailers equipped with air bags. From a dynamic point of view, the effect of suspension type appears to be more significant than the number of axles.

The purpose of this study was to compare the relative behavior of the JXS super-heavy haul vehicle trailer, equipped with an hydraulic cylinder-nitrogen suspension, with that of four currently used semitrailer types. This heavy trailer is capable of carrying 150,000 lb of payload (as tested), distributed over 32 tires (Figure 1). Three semitrailers and a jeep were used for the comparison. Two semitrailers were equipped with tandem axles (one of the tandem trailers had a leaf-spring suspension and the other an air bag suspension), and the third was equipped with a tridem axle using an air bag suspension. The jeep (auxiliary dolly) was equipped with 2 axles (16-tire group) with a walking beam suspension.

One of the new features of the JXS trailers (design by Trans World Crane, Inc., for Jake's Heavy Lift & Transport International) is the configuration of the suspension and the axle (Figure 2). The JXS (Jake's EXtra Speed) axle, developed for use by the heavy-haul transporter at normal highway speeds, can be positioned at various points on the trailer's frame. Because load equalization would be difficult over many axle points on a long and wide structure, it was decided that a suspension having extensive vertical travel in which each axle steers would be necessary. An hydraulic cylinder-nitrogen suspension system satisfied these requirements. The suspension uses a 6-in.-diameter cylinder with an 18-in. stroke and can steer to ±45 degrees. The nitrogen system used was designed to give the vehicle a stability float similar to, but slightly stiffer than, an automobile coil spring suspension.

The Permits Department of CALTRANS (California Department of Transportation) is often asked to issue permits for the movement of unusual vehicle configurations such as the JXS. With the increasing number of these vehicles, it becomes necessary to evaluate the damage they cause. One way to complete this evaluation would be to use the mechanistic design for pavement sections. This method allows comparisons of the relative performance of sections under the influence of these various types of trailers, providing that time histories of the loads applied are known.

The shaking table of the Earthquake Engineering Research Center (EERC) at the University of California Richmond Field Station (RFS) was used to investigate some aspects of the dynamic behavior of trailers. By individually exciting a set of dual tires with known amplitudes and frequencies and simultaneously reading the loads under each set of dual tires, it is possible to determine the frequency response function of the vehicles for the frequency range tested. It is also possible to generate time histories of loads under various types of excitation.

Using the frequency response function of the trailer and the profile of typical highway roads, it is possible to determine the power spectral density of the loads actually applied by each tire. As part of this study, the RPL (Reduction of Pavement Life Index) of each of the trailers was also determined (under specific conditions speed and pavement roughness, i.e., amplitude and frequency of excitation).

TESTING PROGRAM

Equipment and Instrumentation

The principal intent of this research was to compare the performance of various suspension systems and to determine the effects of the suspension and trailer designs on pavement performance. For this reason, eight load cells were used to directly measure the loads applied by each set of dual tires. Wooden blocks were placed beneath the other tires to keep the trailer level.

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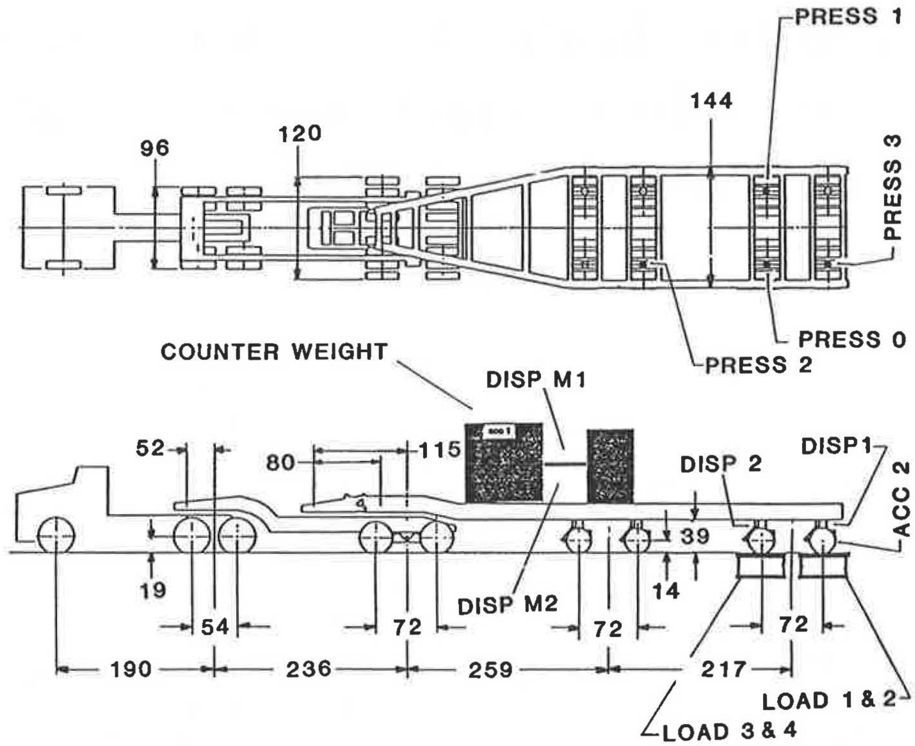

FIGURE 1 JXS trailer on a 9-axle configuration with location of the transducers.

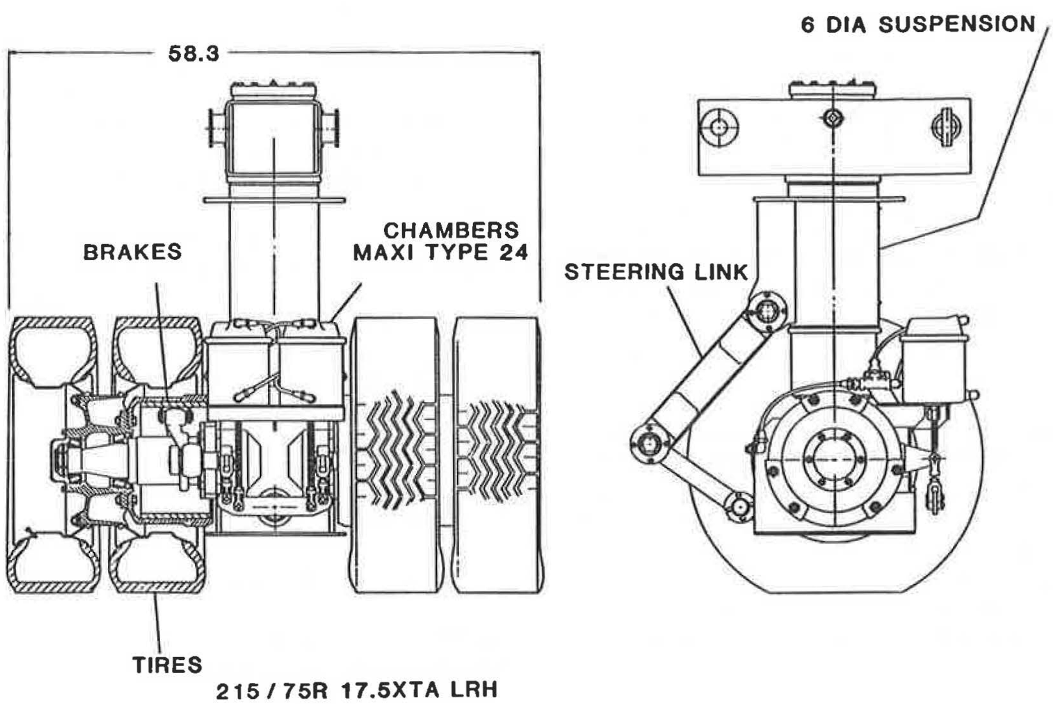

FIGURE 2 JXS axle and piston diagrams.

A beam was fabricated and attached to the shaking table so that the axial movement of the table could be transmitted to a specified set of dual tires (Figure 3). This beam contains two parts. One acts as a major cantilever beam extending out from the shaking table. This cantilever was physically attached to the table by four 60 TF prestressed rods positioned 3 ft apart. The other part is a movable L-shaped cantilever. One side attaches to the major cantilever beam, and the other side contains a load cell (load 1) on top of which a set of dual tires can be placed. A potentiometer (disp b) was placed between this L-shaped piece and the ground floor to measure the actual input displacements to the set of dual tires (this reading should be equal to the vertical displacements of the shaking table plus the deflection of the beams).

An accelerometer was positioned on the top central position of the heaviest counter weights used to ballast the trailers (acc 1). Another accelerometer positioned near the end of the axle being excited by the L-shaped cantilever beam recorded the acceleration.

On the JXS, four pressure transducers were used to record the pressures in the pistons (press0, press1, press2, and press3). Figure 1 diagrams the location of the transducers. Additionally, every piston was instrumented with a potentiometer to record the displacements (disp 1 through disp 8) and two additional accelerometers were positioned at each end of the trailer to help identify modal frequencies. During the tests on conventional trailers the number of channels was reduced.

Testing Sequence

Several tests were performed on each trailer. To determine the frequency response function (*1,2*) of a trailer it is necessary to excite it with known sinusoidal amplitudes and frequencies and monitor its response. Several frequency response functions can be obtained for a single vehicle. Essentially these functions can be perceived as black boxes. From one end known frequencies and amplitudes are input, and from the other end the responses are measured.

In this study the inputs were the amplitudes and frequencies of the displacements applied to a selected set of dual tires. The monitored responses essentially represent the time variation of the loads under the tires and the time variation of the vertical accelerations of the counter weight(s) placed on the trailers. The frequency response function of the load under the set of dual tires being excited was determined for each trailer. Several other frequency response functions can also be derived from the data obtained.

The experimental work was subdivided into testing sequences. A detailed description of the test sequences has been presented previously (*3*). Generally each sequence of tests contained at least one test with a random input with a white noise acceleration (the amplitude of the acceleration is the same at all frequencies) within the frequency range of interest (0 to 20 Hz) and a series of tests composed of sinusoidal inputs between 0.8 and 20 Hz. During each sequence all characteristics of the trailer being tested remained the same. During these sequences about 40 Mbytes of data were collected. In this paper only selected aspects of the data analysis are presented.

DATA ANALYSIS

Determination of the JXS Piston's Friction

During the initial stages of testing, the piston exhibited slip/stick behavior under sinusoidal input; in other tests, it did not exhibit any displacement. This irregularity was attributed to piston friction caused by the bearing or the seals, or both. To determine the magnitude of the friction forces, data were interpreted from tests in which the piston moved. To minimize errors caused by inertia forces, a low-frequency test (1.5 Hz) was selected for analysis.

Figure 4 displays the time variation of the force applied to the piston, the piston displacement, and the pressure variation in the piston. From the displacement trace the slip/stick pattern can be observed. The variation in the oil pressure, caused by the sudden movement of the piston, can be identified in the pressure trace. The force variation indicated variations of approximately ± 1.0 kip.

Studying the data that were gathered between 0.48 sec and 0.75 sec confirms that the piston did not move while the force was steadily increasing (roughly between -0.8 klb and 1.0 klb). The piston did not move until enough force was present to break the frictional forces.

For this case it can be assumed that

$$\text{Force}_{(\text{friction})} = \text{Pressure}_{(\text{piston})} * \text{Area}_{(\text{piston})} - \text{Force}_{(\text{tires})}$$

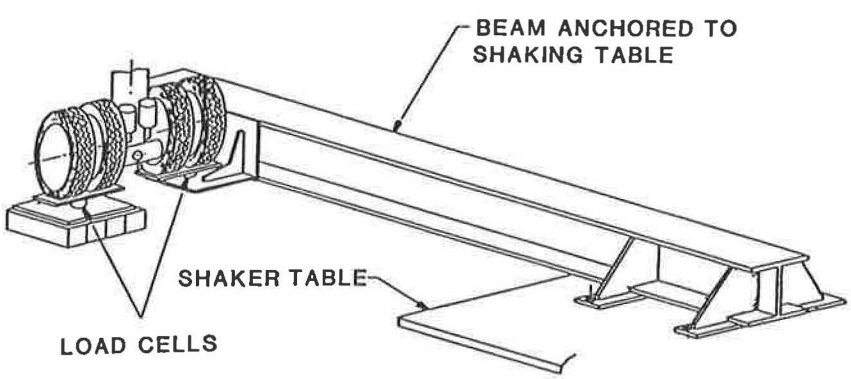

FIGURE 3 Schematic representation of the I-beam extending from the shaking table to transmit excitation to a set of dual tires.

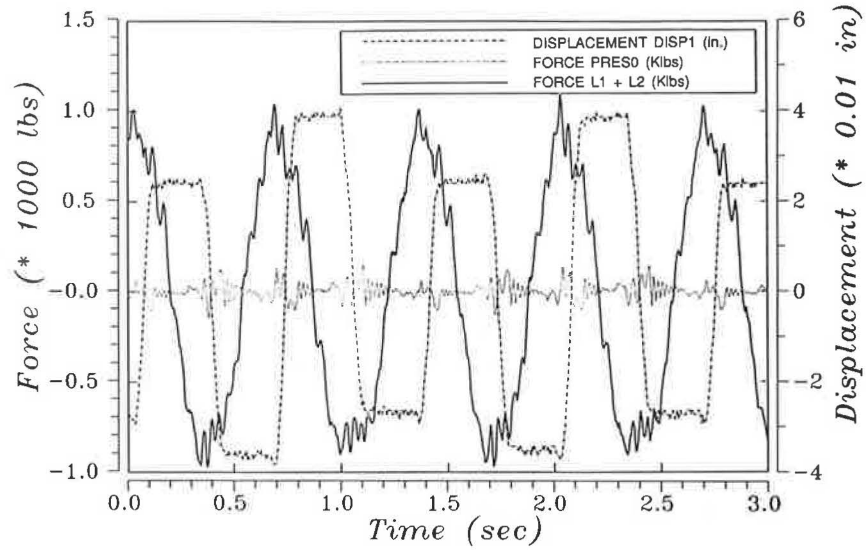

FIGURE 4 Time variation of displacements, pressure, and forces for PISTON I at 1.5 Hz.

Figure 5 plots the time variation of the friction force for this case (identified as the trace of Piston I). The figure indicates that the frictional forces can be as high as 2 klb.

Based on this finding, the piston (Piston I) was replaced by another (Piston II) in which the bearing and seals were machined to higher tolerances and lubricated. Figure 6 graphs the time variation of force displacements and pressure for Piston II under the same conditions as for Piston I. The slip/stick behavior is still present, but the force necessary to break static friction is now of a lower magnitude.

Figure 5 compares the variation of the frictional forces with time, for both pistons. The magnitude of the friction forces in Piston II was reduced to about 600 lb. The magnitude of the force caused by pressure variation is quite small, accounting for only about 200 to 300 lb of the load. The predominant frequency present in the traces is 24 Hz, probably because of the oil column resonance in the hydraulic lines.

Effects of Piston Friction

Dynamic Effects

The effects of friction can be both beneficial and detrimental to vehicle performance. Figure 7 shows the frequency contents of the acceleration for the counter-weights placed on the JXS system. For each frequency the graph indicates the amplitude of the accelerations caused by a random input on the left rear piston.

The trace, represented by a solid line, was obtained with Piston I. It is clear that there are two predominant frequencies, one at 2 Hz and the other at 7.5 Hz. A few additional peaks can be identified at 6.5, 9, 11, and 24 Hz.

For Piston II the trace is quite different. The peak at 2 Hz is still present; however, the peak at 7.5 Hz no longer exists. Peaks at 5.0, 6.5, and 11.0 Hz are now noticeable. The response

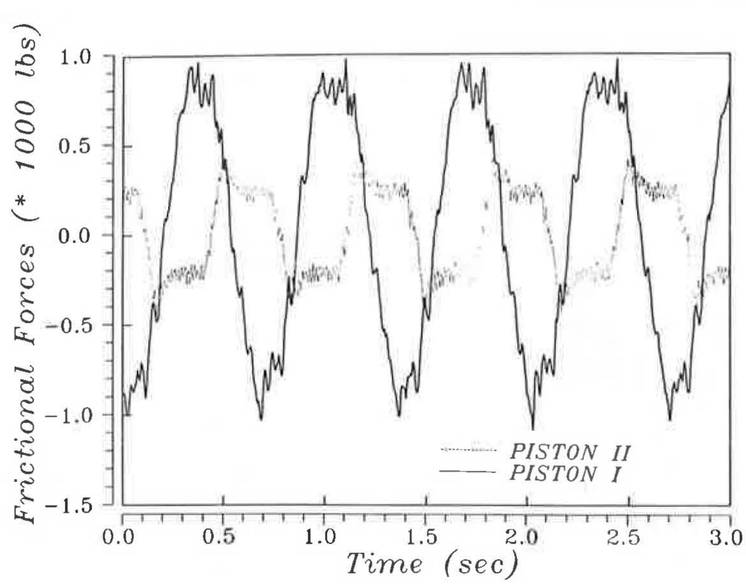

FIGURE 5 Time variation of frictional forces for PISTON I and PISTON II.

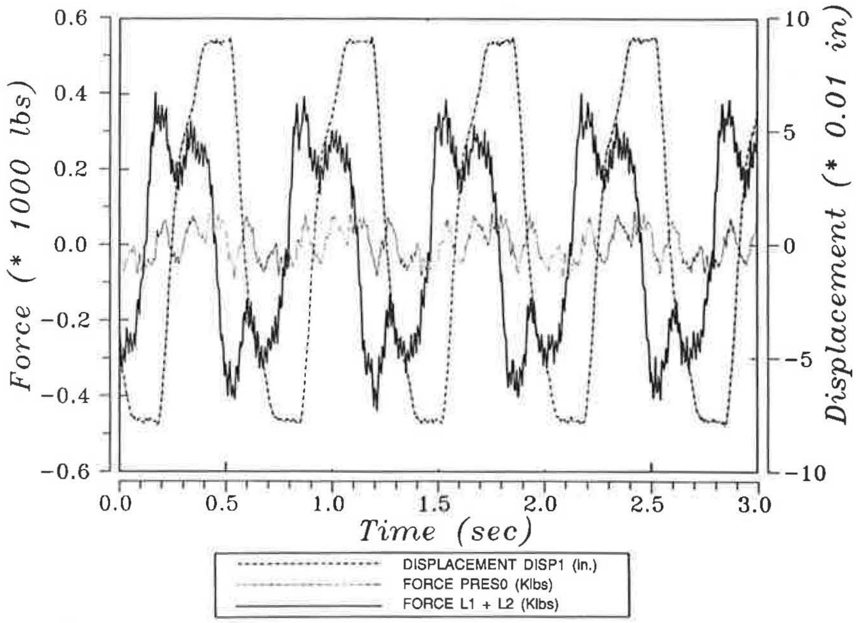

FIGURE 6 Time variation of displacements, pressure, and forces for PISTON II at 1.5 Hz.

of the vehicle, except for the decrease in performance at 11.0 Hz, is improving by offering a "softer" ride.

Static Effects

Before the tests were executed at RFS, the tractor/trailer combination stopped at scales during the trip from Las Vegas to Richmond. Table 1 shows the values of the weight obtained from each axle. These values show that the air bag and the walking beam suspensions provided a good load axle distribution. However, the JXS exhibits axle load differences as high as 5,580 lb.

During the tests the friction for Piston I was measured at 2,000 lb. Therefore, the maximum load difference between the two axles can be as high as 8,000 lb (2 pistons × 2 axles × 2,000) (note that each axle on the scale encompasses two JXS axles or two pistons). These values are of the same order of magnitude as the values recorded by the scales.

Based on the results obtained from the shaking table, all pistons on the JXS where modified, and a series of static tests were later performed by CALTRANS in Las Vegas, Nev., to investigate if load distribution characteristics had improved. Column 3 shows typical results obtained by driving the JXS on to the load cells. Significant improvement has been achieved by reducing the piston's friction levels.

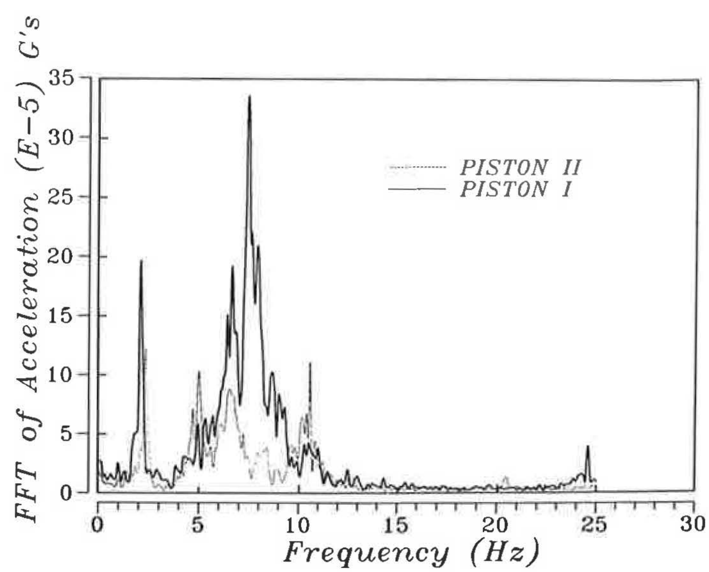

FIGURE 7 Comparison of the accelerations on counter weight for PISTONS I and II.

TABLE 1 AXLE WEIGHTS OBTAINED AT WEIGH STATIONS

	(1) SCALES A (10E3 LBS)	(2) SCALES B (10E3 LBS)	(3) NEW PISTONS (Load Cells) (10E3 LBS)	(4) REMARKS
AXLE 1	17.0	17.16		FRONT AXLE
AXLE 2	20.2	21.08		
AXLE 3	20.3	20.08		AIR BAGS
AXLE 4	22.4	22.66		
AXLE 5	21.6	21.92		WALKING
AXLE 6	23.4	23.78	30.20	
AXLE 7	26.7	27.02	30.46	
AXLE 8	29.2	28.90	30.02	JXS
AXLE 9	28.3	29.36	29.30	

Investigation of Nonlinearities in Vehicle Response

Three levels of random displacements were provided to the JXS trailer at the rear left piston. Figure 8 diagrams the time history of the displacements measured with the potentiometer disp b (located between the L-shaped piece and the ground floor). It can be observed that the three traces are of similar shape, differing only by the amplitude (600, 500, and 100).

During these tests the acceleration of the counter weight was recorded. The fast fourier transform (FFT) of this acceleration was divided by the FFT of the input displacements (Figure 9). If the trailers had linear response the three traces would be superimposed.

Although the trace displayed reaches up to 30 Hz, the most meaningful fraction is between 0 and 12.0 Hz. Beyond this range the noise levels are of the same magnitude as those of the components, thus affecting the interpretation.

These results indicate that a typical frequency response analysis of truck behavior cannot be performed in this study because this type of analysis assumes a linear response for the structure being studied. However, this approach could be implemented to evaluate suspension and vehicle behavior if input levels in laboratory studies are within those provided by normal highway operations. Unfortunately the amplitude/frequency ranges that could be provided by the shaking table do not cover the full spectrum that can be encountered in rough pavements.

Response of the Trailers to Random Input

One particularly interesting variable is the capability of a trailer to minimize the level of acceleration induced to the payload. Figures 10 through 13 compare the FFT of the vertical acceleration recorded on the counter weights for the various trailers. At the lower frequency ranges the JXS outperforms the other trailers. In the higher frequencies (i.e., 5 to 12 Hz) the walking beam and the air bag 3 exhibit better

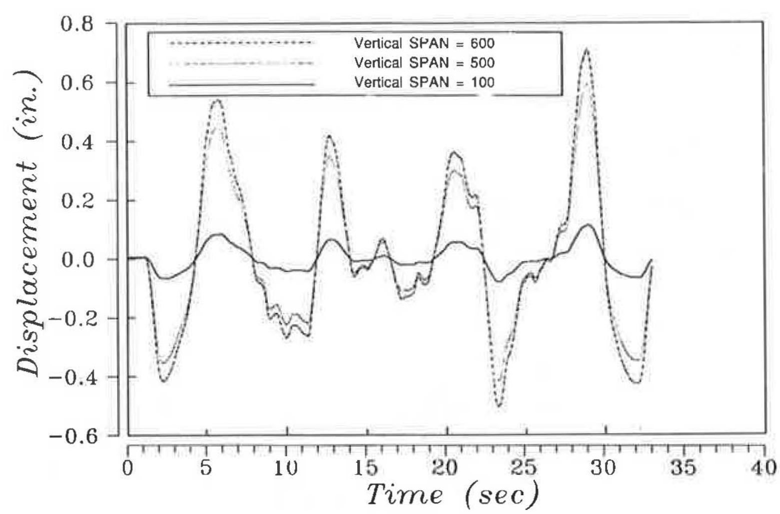

FIGURE 8 Time histories of the input displacement for three different levels of vertical SPAN.

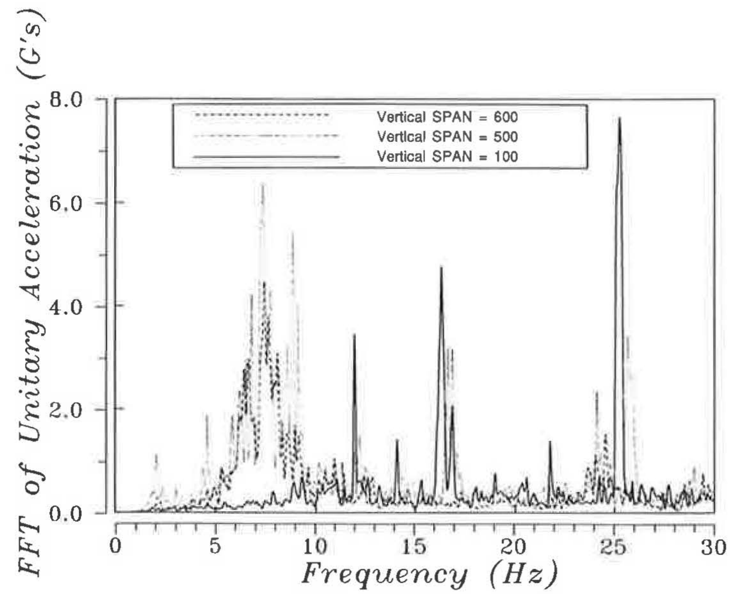

FIGURE 9 FFT of the relative accelerations of the counter weight for the three levels of input displacement.

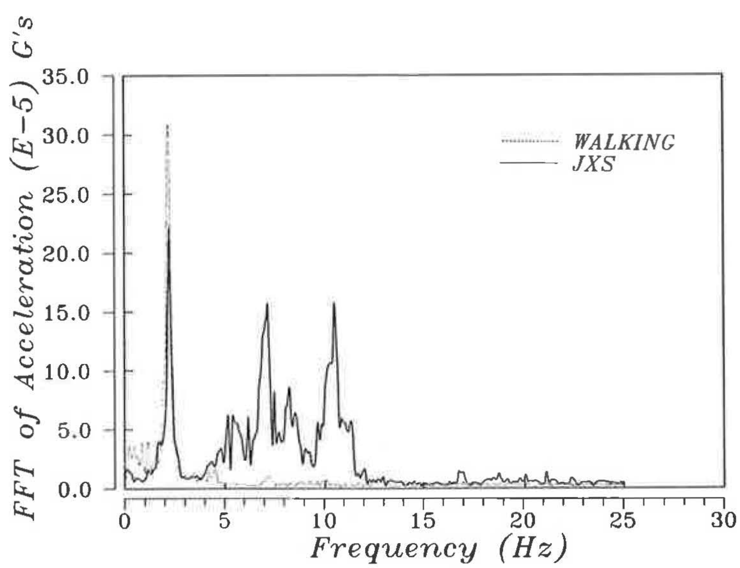

FIGURE 10 Comparison of the accelerations of counter weight between the JXS and the WALKING BEAM.

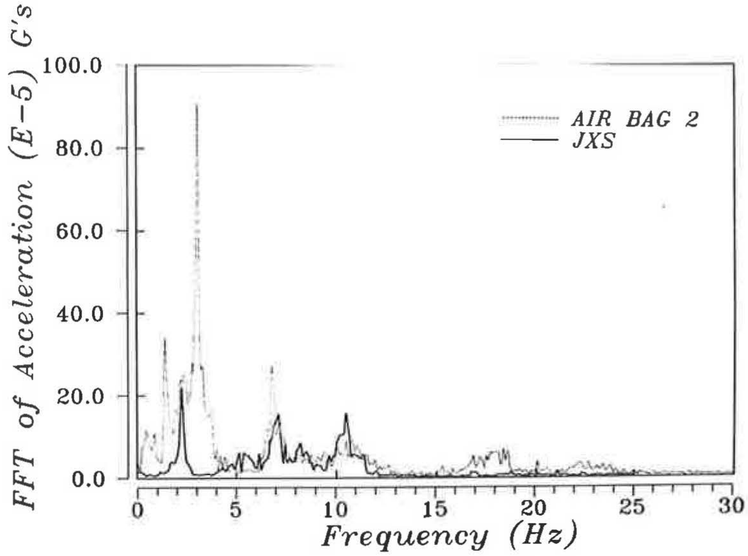

FIGURE 11 Comparison of the accelerations of counter weight between the JXS and the AIR BAG 2.

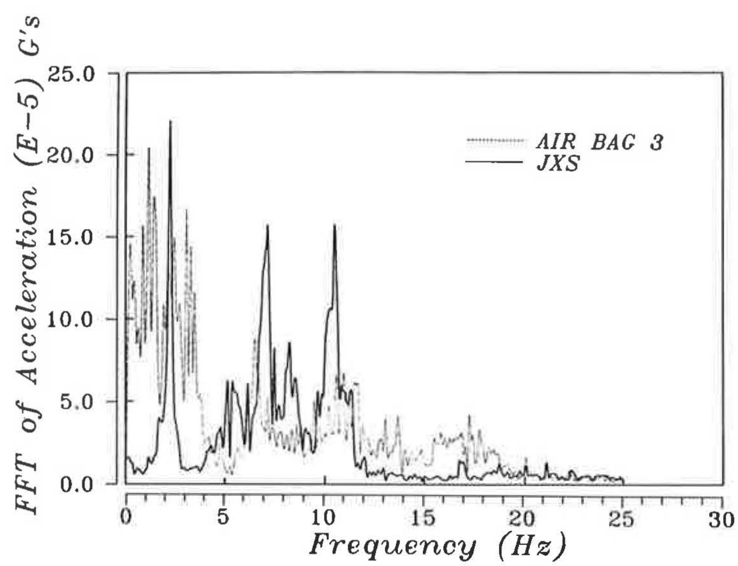

FIGURE 12 Comparison of the accelerations of counter weight between the JXS and the AIR BAG 3.

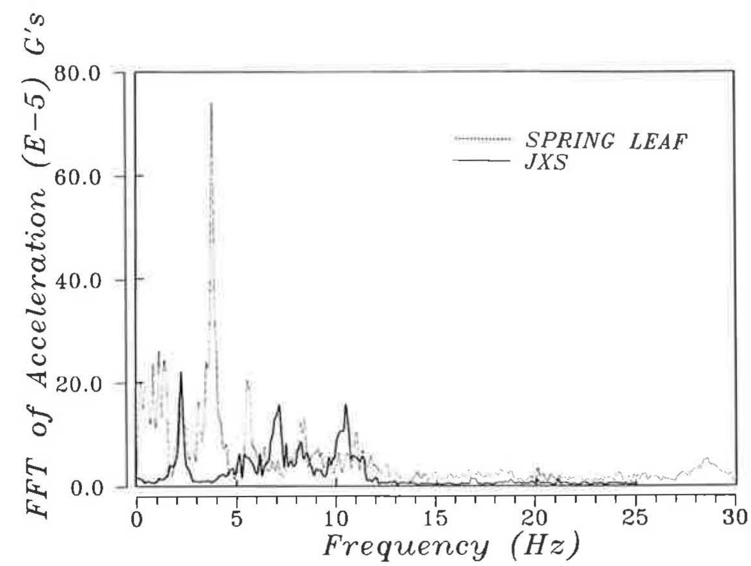

FIGURE 13 Comparison of the accelerations of counter weight between the JXS and the LEAF-SPRING.

performances. The comparison with the walking beam is not quite appropriate because the jeep equipped with the walking beam was of very small dimensions. Resonance frequencies caused by a long frame (such as the JXS or even the other semitrailers) are not present within the frequency range studied. Furthermore, the dimension of the counter weight was such that it almost totally covered the jeep, thus preventing the excitation of any resonance mode in the frame.

The data also suggest that generally the leaf-spring semitrailer exhibits the worst performance.

Determination of the Frequency Response Functions

To evaluate its behavior to dynamic inputs, the behavior of JXS was compared with that of other trailers. For each trailer the same input (displacement of dual right rear tires) was imposed at various frequencies. Figure 14 graphs the input for each of the trailers. The shaking table is unable to provide displacements of high amplitudes at high frequencies; therefore, the amplitude at 1 Hz was 0.25 in. and at 12 Hz was, at most, 0.025 in.

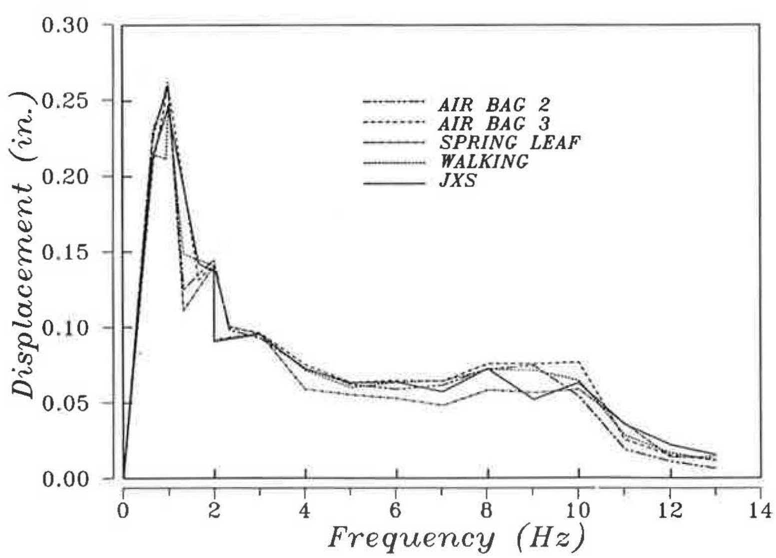

FIGURE 14 Input displacement amplitudes for sinusoidal excitation, applied to the trailers (function of frequency).

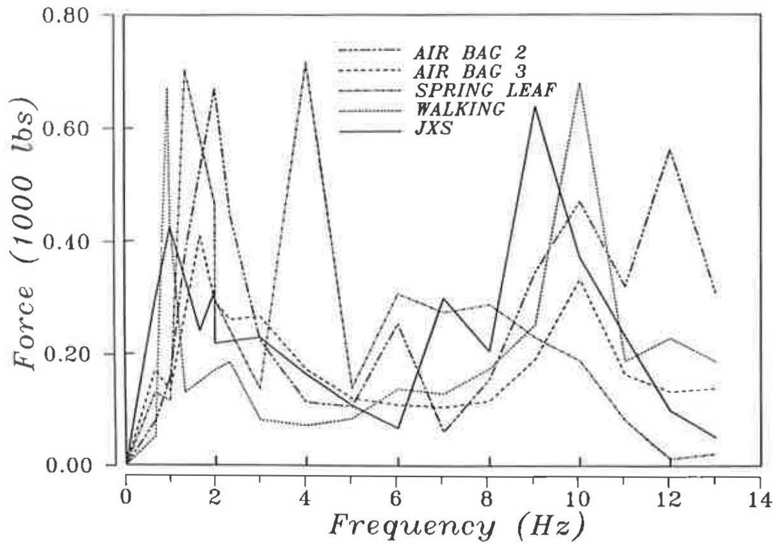

FIGURE 15 Force amplitude obtained from the frequency sweep for load 1 for all trailers.

Figure 15 displays the values obtained for the force ($L1$) (see Figure 1) under the dual right tires for the various trailers.

Two major peaks can be globally identified, one at about 1 to 2 Hz and the other at about 9 to 12 Hz. The first corresponds to the body's predominant mode of vibration and the second to the predominant frequency resonance of the suspension (axle assembly). In the case of JXS, it is possible that in the high frequency range (9 to 12 Hz) flexure and torsional modes might be present.

Figure 16 shows the frequency response function $H[L1/b](w)$ [or force amplitude ($L1$)/Input Displacement Amplitude (b)] (in pounds per inch) so the responses of various trailers can be compared. It is the frequency response function at each frequency of each of the trailers for the load analysis. Essentially these traces indicate the magnitude of the dynamic load that would be produced (if linearity is assumed) by sinusoidal displacement with 1 in. of amplitude imposed at the tires.

These values indicate that the dynamic component of the loads that can be expected for the JXS are within the same order of magnitude as the loads produced by any other trailer. The solid trace presents the peaks at 7 Hz and the other at 9 Hz, indicating the frequencies that are most unfavorable for the JXS. For the lower frequency range, which is most likely to be encountered on normal highway conditions, the JXS mostly offers the same or better load response. It is also noticeable that the airbag 2 exhibits the worst performance

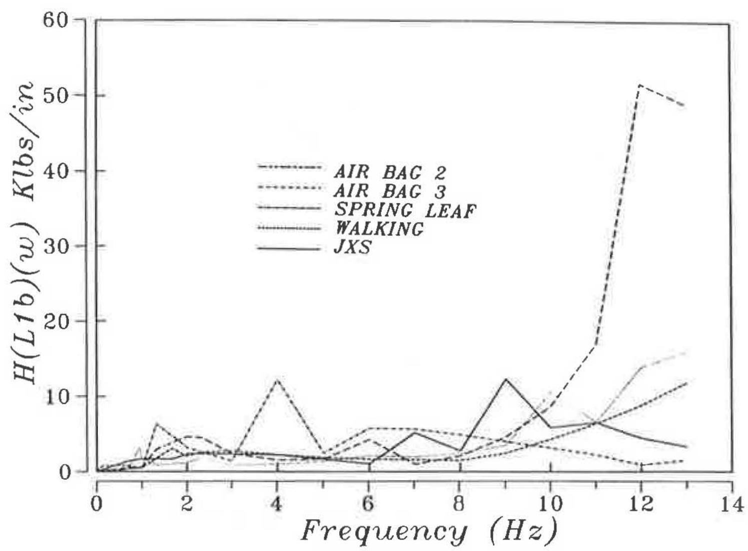

FIGURE 16 Frequency response function of the various trailers.

at about 12 Hz. Although air bags are generally chosen because they offer a softer ride, that does not necessarily imply benign effects to the pavement.

On-the-Road Performance of the JXS

After JXS was laboratory tested, its performance on the highways was investigated so that some of the observations made on the shaking table could be validated.

The following transducers were mounted on the JXS trailer:

- One accelerometer recorded the vertical acceleration of the heaviest counter weight.
- One accelerometer recorded the vertical acceleration of the right rear axle. The accelerometer was positioned at the middle of the axle, just beneath the piston.
- One accelerometer was positioned at the center rear end of the frame to measure vertical acceleration.
- The four pressure transducers used during the testing sequences remained in position. They were used to monitor pressure variations in the piston.
- Eight potentiometers monitored the displacement of the pistons. Unfortunately, data from the transducers cannot be used because the file containing the calibration contents was lost.

The transducers were excited by a very low-noise alternating current (AC) signal conditioner. All data were recorded by an on-board TOSHIBA 3200 portable microcomputer. The 115 AC power supply was provided by a gasoline generator. A line tamer was used to stabilize the current. The data acquisition software permitted the continuous recording of 4.8 sec of data at a rate of 200 conversions per sec per channel with 12-bit accuracy. A Metrabyte DAS16F board performed the analog to digital conversions.

The road test was executed on Tuesday, June 21, 1988, between 6:00 and 7:00 p.m. on Interstate 80 between the Richmond Field Station and the Cordelia scales. At this time traffic was heavy and maintaining speed was difficult. Therefore, the velocity information ascertained with the data is not accurate. For example, during preparation of a file to receive data obtained at speeds of 55 mph on rough pavement, the speed dropped to about 20 mph. Therefore, all data associated with this section are presented with reservations.

There was an attempt to include information in the data files about respective roughness levels and speed. The experts on roughness were the drivers of the trucks. They were asked to characterize roughness levels on a scale of 0 to 5 (0—very smooth, 5—very rough). The speed was read directly from the speedometers of the trucks. From all the various data records only two are analyzed here. One was obtained at approximately 55 mph over a jointed rough PCC pavement section. The other was obtained at about 25 mph over a relatively smooth asphalt pavement.

Figure 17 graphs the FFT of the vertical accelerations of the counter weight. At lower velocities, the accelerations are kept at levels below 0.02 *g* with peaks at 1.5, 2.8, 8.0 and 11.0 Hz, peaks at frequencies close to those identified with the shaking table. Note that these peaks are not expected to agree with those obtained by the shaking table because on the freeway the counter weight is subjected to a multitude of inputs (one for each tire).

At roughly 50 to 60 mph on a rough PCC pavement a very strong peak can be observed. Although the spacing of the joints is the cause of the peak (clearly if the pavement were perfectly smooth no vibrations would be noticeable) the fact that it occurs at 9 Hz is because of the physical characteristics of the JXS. This resonant frequency was also observed during the tests on the shaking table especially when Piston I was present. This could be caused by the friction still present on the other pistons. The cause of the resonance frequency at 9.0 Hz is not because of the presence of friction in the piston; instead it is because of the size, weight, and physical characteristics of the JXS frame. The friction causes the excitation at that frequency by preventing the free movement of the pistons that lock and, therefore, directly transmit the excitations to the frame from the road. If the friction were reduced this peak might not be as high. Figure 7 shows the acceler-

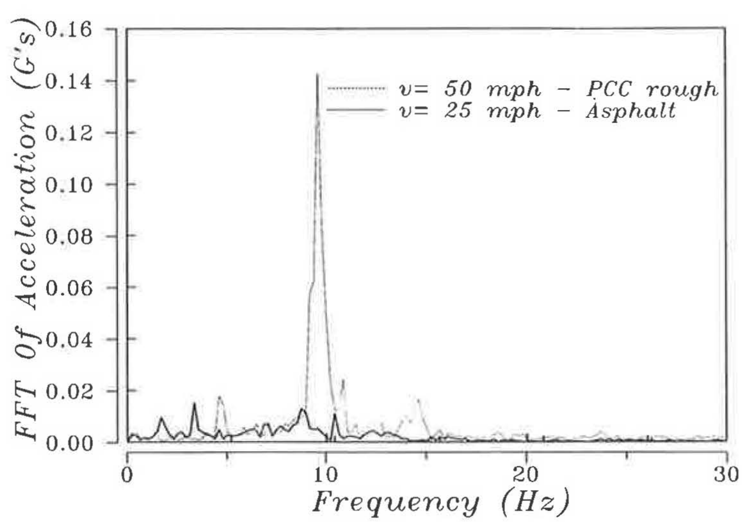

FIGURE 17 FFT of accelerations of the counter weight placed on the JXS for two on-the-road conditions.

TABLE 2 STATIC LOADS UNDER VARIOUS SUSPENSIONS

(1) LOAD (KIP)	(2) AIR BAG2	(3) AIR BAG 3	(4) LEAF-SPRING
L1	4.58	4.55	5.39
L2	4.99	4.23	6.55
L3	3.81	3.91	1.22
L4	4.60	5.13	2.61
L5		4.13	
L6		6.00	
MEAN	4.49	4.65	3.94
VARIANCE	0.24	0.61	5.99

ations of the counter weight recorded during the tests with Piston I and Piston II on the shaking table. The effects of reduced friction are quite noticeable.

Load Distribution Characteristics of the Various Suspensions

Load distribution characteristics can be examined from a static or a dynamic point of view. The first applies, for instance, when a vehicle slowly goes over a curb with a set of dual tires and stays there. The other is applicable for a moving vehicle going over, for example, a pothole or a step fault on a PCC pavement. This analysis was performed only with the data obtained from the semitrailers equipped with air bags and leaf-spring suspension as they are standard configurations.

Table 2 displays the static component of the load for the various vehicles. These are the mean values of the static load recorded for an input sinusoidal excitation at 1 Hz. The static values for other frequencies were also investigated with similar values of variance and mean. It is clear that the leaf-spring suspension has the poorest static load distribution characteristics. (Note: the load cells were placed under the tires by individually raising each axle with a jack.)

To investigate the sharing capabilities of a suspension in a dynamic environment an approach similar to that described in On-the-Road Performance was followed.

The dynamic load ratio was defined as

$$DLR(w) = \sum_{i=1}^{i=N} Amp_{(i,w)} \Big/ \sum_{i=1}^{i=N} Sta_{(i,w)} \quad (1)$$

where

i = a dual set of tires;
N = the number of sets of dual tires on the suspension;
$Amp_{(i,w)}$ = amplitude of the dynamic component of the load applied by dual set of tires i at frequency w; and
$Sta_{(i,w)}$ = the mean value of the load (static component) applied by the set of dual tires i.

Essentially the sum of the dynamic components of all the loads applied by the tires is divided by the sum of the static components of the same loads. A DLR of 0.30, for instance, indicates that the magnitude of all the dynamic loads was 30 percent of the static loads. This value implies that the loads transmitted to the pavement can be as high as 130 percent of the static load and as low as 70 percent.

Generally a good suspension will minimize the DLR, whereas a bad suspension will induce higher dynamic components of the load on all tires, thus causing a higher value for the DLR.

Two factors can contribute to a high DLR: (a) the suspension is such that it causes high components of dynamic load, and (b) the suspension does not provide a good equalization of the load among the tires. It is difficult to identify which of those two factors plays a more important role in a high DLR. Figure 18 graphs the variation of the DLR with frequency for the various vehicles. The leaf-spring suspension clearly presents the worst performance. The DLR for this suspension is higher at almost all frequencies. The air bag 2 performs relatively well, except at 2 Hz, where the roll mode of resonance induces high dynamic loads, imposing very poor load distribution, and at 12 Hz at the natural frequency of the axles.

Comparing the shape of the curves in Figure 18 with those in Figure 16, it is apparent that the dynamic components on the set of tires not being excited contribute strongly to a high DLR for the leaf-spring. This value can be caused by poor load distribution capabilities.

The DLR depends on the frequency of the load (for sinusoidal inputs) as observed in Figure 18. If the DLR were computed only at 6 Hz, for example, the $DLR_{airbag3}$ would be higher than the $DLR_{airbag2}$; however, at 10 Hz the order is reversed. These data imply that if suspensions or trailers are compared based on ratios of this type, obtained from their responses when traveling at a given speed on a given pavement profile, the conclusions cannot be extrapolated to other speeds or other pavement profiles or even to other payload levels.

PAVEMENT PERFORMANCE CONSIDERATIONS

For specific pavement types, it is important to decide which modes of distress contribute to pavement deterioration and, therefore, to a reduction in pavement serviceability. For asphalt pavements, the major modes of distress directly associated with load are fatigue, cracking, and rutting. For portland concrete cement pavements, step faulting at the joints (in undoweled pavements) and fatigue cracking appear to be the major causes of loss in serviceability because of traffic loadings.

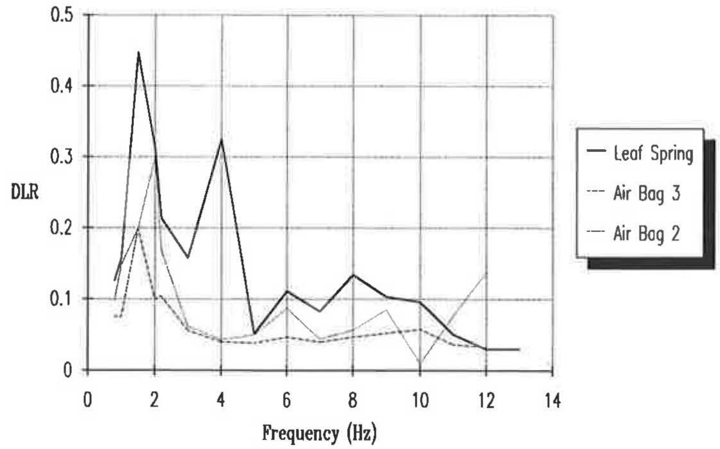

FIGURE 18 Variation of DLR with frequency for three semitrailers.

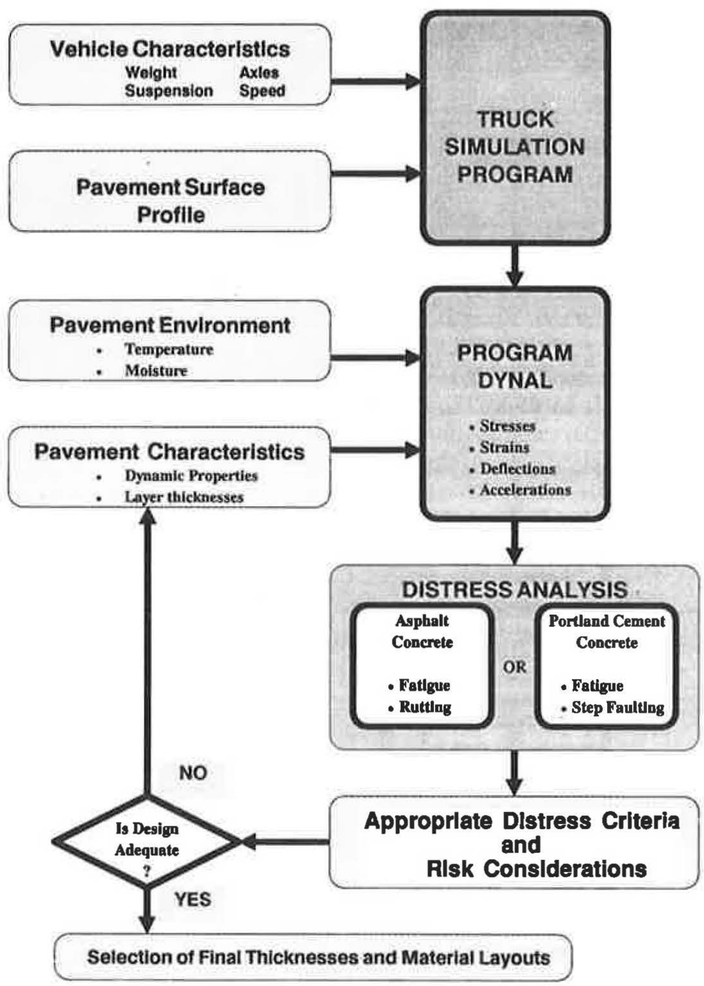

FIGURE 19 Diagram for analysis of a pavement section.

As seen in Figure 19, analysis of a specific pavement section involves determining if the section under consideration will be able to sustain the anticipated loading; if not, a new section must be selected and checked.

To illustrate the process, consider fatigue analysis. Results of studying the fatigue response of asphalt concrete indicate that the following expression is a reasonable damage determinant (*4*).

$$\log N_f = 15.947 - 3.291 * \log(E_t/10^{-6}) - 0.854 * \log(S_{mix}/10^3) \quad (2)$$

where

N_f = number of load applications to 10 percent cracking,
E_t = tensile strain (resulting from load) repeatedly applied, and
S_{mix} = dynamic stiffness modulus of the asphalt bound layer.

The program ELSYM (*5*) can be used to ascertain strains resulting from anticipated static loads. According to the above expression, for a particular strain level there is a number of load repetitions (N) that can be sustained before cracking takes place. Since there will be a range in loads and thus in strains, the cumulative effects of the various strain levels must be considered. This can be done by using the linear summation of cycle ratios cumulative damage hypothesis:

$$\sum_{i=1}^{n} (n_i/N_i) = 1 \quad (3)$$

where

n_i = actual number of load repetitions at strain level i, and
N_i = allowable number of load repetitions at strain level i (from Equation 2).

When the linear sum of cycle ratios reaches unity in this expression, the pavement is no longer considered serviceable and rehabilitation is required.

The objective of the design process is to find a suitable combination of materials and layer thickness that permit the anticipated loads to be carried for a prescribed period of time.

As seen from the above discussion and from the illustration (Figure 19), there are essentially four steps in the process for defining representative interactions between a vehicle (truck) and the pavement. They are

1. Definition of vehicle characteristics through direct measurements of response, e.g., through the use of the shaking table, a simulator like that developed by PACCAR (*6*), or by means of computer analysis using truck simulation programs such as RIDE (*6*) or DYMOL (*7*).
2. Definition of representative pavement profiles.
3. Definition of the pavement response to the loads generated from items 1 and 2.
4. Definition of adequate distress analyses and distress criteria for representative pavement materials.

Comparative analysis can be performed by keeping some of the variables constant and varying others. Two such comparative analyses were undertaken to evaluate the relative behavior of the trailers tested. They are as follows:

1. Mechanistic quasi-static analysis—considered the relative effect of the various levels of strain caused by the various trailers, assuming no dynamic effects, that is, truck loads were assumed to be applied on an infinitely smooth pavement surface.
2. Determination of the RPL index for each trailer (*8*)—looked separately at the dynamic effects of the suspension on pavement damage (life) for the same time history of input displacement.

Mechanistic Quasi-Static Analysis

To investigate the relative effects of the loading level and spacing between loads (tires) on pavement performance, a typical asphalt concrete pavement section was selected (see Table 3). The 12-in.-thick asphalt layer was subdivided into two layers so that different temperature could be simulated.

The computer program ELSYM was used to determine the maximum tensile strain on the bottom asphalt layer for the loads imposed by each of the trailers. The columns of Table 4 display the intermediate steps (columns 1 through 7) and final result (column 8) of this analysis.

TABLE 3 PAVEMENT SECTION USED FOR ANALYSIS

(1) LAYER	(2) PROPERTIES
Asphalt Concrete	H = 6 in. ν = .15 E = 800 000 PSI
Asphalt Concrete	H = 6 in. ν = .10 E = 1 200 000 PSI
Base	H = 6 in. ν = .35 E = 10 000 PSI
Subgrade	ν = .35 E = 5 000 PSI

TABLE 4 DETERMINATION OF THE TOTAL WEIGHT (lb) TRANSPORTED BY EACH TRAILER DURING A PAVEMENT LIFE

(1) TRAILER	(2) # Tires Susp.	(3) Load (lbs) (E+03)	(4) MAX Strain (E-04)	(5) # rep. Failure (E+06)	(6) #rep/ pass (E+06)	(7) # passes	(8) lbs transp./ pavement life (3)*(7)(E+9)
Single	4	18	.649	22.557	1	22.6	**406**
Tandem	8	34	.574	33.791	2	16.9	**574**
Tridem	12	42	.510	49.861	3	16.6	**698**
Walking beam	16	60	.780	12.317	2	6.2	**370**
JXS-12	16	60	.683	19.067	2	9.53	**572**
JXS-14	16	60	.641	23.497	2	11.75	**705**

The data for column 5 were obtained by introducing the values of column 4 into the formula (formula 1). This value represents the number of times that an axle of the trailer could pass over that pavement section. The estimated number of passes of a trailer (column 7) was obtained simply by dividing that number by the number of axles (column 6), given that the maximum strain occurred under that axle.

Most analyses stop at this stage, and trailers or suspensions are compared based on the number of repetitions to failure on a particular pavement. According to this approach, the trailer equipped with a single axle would be recommended for yielding the maximum number of repetitions ($N = 22.6 \times 10^6$). However, the main purpose of a road is not to withstand repetitions but to provide the means by which a payload can be transported from point A to point B. Therefore, an alternative method for comparing trailers is to compute the amount of payload they could carry over the life of a pavement. This value can be obtained by multiplying the number of passes the pavement can withstand by the total load carried with each pass (column 7).

It is now clear that a JXS-14 (14 ft overall width) would be capable of carrying more load over the life of the pavement section studied than any other trailer. In fact, it could carry twice that carried by a trailer equipped with a single axle. The jeep equipped with the axle walking beam (16-tire group) appears to be the least effective with only 370×10^9 lb carried versus 704×10^9 lb for the JXS-14.

These values are specific for the pavement section studied. The results presented are only relative to the California Department of Transportation permit program and may not be the same for other states. For a complete evaluation of the relative performance of the trailers several other pavement sections should be investigated under different conditions (i.e., temperature and moisture content) and also for PCC pavements. Such studies were beyond the scope of this project.

Determination of the RPL Index for Each Trailer

This section investigates the effects of the dynamic loads generated by each of the trailers on pavement performance. Determining the relative damage effects of the five types of trailers could be completed in three steps:

1. Determination of the time histories of the tensile strain at the bottom of a representative pavement structure using dynamic material properties. The strains can be computed using a new computer code, SAPSI (*9*), developed by Chen and Lysmer. This code 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 generally accepted fatigue criteria. For each of the trailer types, the number of load applications to failure can be computed. The linear summation of cycle ratio cumulative damage hypothesis (Miner's Hypothesis) can be used to assess the relative damage imposed at each level of strain.
3. For purposes of comparison, a reduction of pavement life index (RPL) can be developed for each trailer type. Each RPL value represents the percentage of pavement life consumed solely by the dynamic effects imposed by one type of trailer (*8*). The definition of the RPL is as follows:

$$RPL(\text{trailer}) = 1 - N_F(\text{trailer})/N_F(\text{static}) \qquad (4)$$

where

N_F(static) = number of load applications to failure computed by current quasi-static methods and
N_F(trailer) = number of load repetitions to failure (taking into consideration the dynamic effects of the suspension).

During this analysis it must be assumed that the dynamic loads produced by the trailer on a rough surface are 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. In addition, it has been shown (*9*) that velocity effects of a moving load (velocity 0) on a layered structure can be assumed negligible for velocities up to 70 mph.

Chen showed (*9*) that it is not necessary to take into consideration the inertia effects of the pavement when determining the time histories of the strains caused by dynamic loads. This permits the use of a simpler static linear elastic layered program like ELSYM instead of the use of SAPSI. Stresses, strains, and deflections can be calculated by the quasi-static procedure described previously.

The approximate time history of the response (stress, strain, deflection) of the pavement can be obtained by multiplying the response to a unit static load by the intensity of the load at each time step. It is important, however, to use the actual dynamic load history and material properties associated with the specific loading conditions to conduct this simplified analysis.

Given that this is just a comparative study between trailers, the material properties of the pavement can also be assumed. However, to determine the RPL for the various trailers, the time histories of the loads produced by the random excitation applied by the shaking table were used, specifically, the load produced by the tandem tires being directly excited (L1).

For this comparative analysis, because of the variance in number of wheels, axles, and axle and wheel spacing, it must be assumed that a pavement section is specially designed for each of the trailers so that the maximum static strain applied to the bottom layer of the individual pavement section would be the same in each of the sections. Since uniform static strain can now be assumed, it is possible to determine the dynamic effect of each trailer type. To specifically focus on a comparison of the dynamic behavior of the various trailers, it was assumed that they would all cause the same static strain, 0.0001.

Since the strain is proportional to the load, time variations of the load would produce proportional time variations of the strain. With this in mind it can be concluded that $L_1\ (t)$ (the time history of the loads in L_1) can be converted to $e_1(t)$ (the time history of the tensile strain on the bottom of the asphalt layer for this trailer) by

$$e_1(t) = 0.0001 * L_1(t)/\text{mean}\ (L_1(t)) \tag{5}$$

Therefore, during the 33 sec of strain, time histories at 200 sample/sec, 6,600 digitized strain levels were obtained.

The attainable number of repetitions to failure was computed using the fatigue law discussed in Mechanistic Quasi-Static Analysis. The RPL values obtained for the various trailers are as follows:

Trailer	*RPL (%)*
Quasi-static	0.0
JXS (Piston II)	0.73
Walking beam	0.76
Spring-leaf	1.11
Air Bag 3	0.92
Air Bag 2	0.77

With these assumptions in mind it is clear that if there were no dynamic effects, all trailers traveling in their own pavement section would each yield the same pavement life. This pavement life would be the quasi-static life. However, the time variation of the strains causes various levels of pavement life consumption with each pass. The most "benign" is the JXS (0.73) followed by the walking beam. The most destructive is the spring-leaf (1.11).

For normal highway operation, RPL values can be as high as 40 percent on very rough pavements and at higher traveling speeds (*8*). The values obtained in this analysis varied between 0.73 for a JXS and 1.11 for the trailer equipped with the leaf-spring suspension. These significantly lower numbers are because the random (white noise) displacement under the set of dual tires was not sufficiently high to simulate that type of highway operation. Furthermore, only one set of tires was excited. On normal highway operations all tires are simultaneously excited. Because of these two factors, the relative difference of RPL values obtained for the various suspensions and axle configurations can be considered significant, indicating different levels of performance. It is expected that larger RPL values and larger differences would be obtained if a high-speed test over a rough pavement were simulated. The relative difference may, however, be different because of nonlinearities in suspension behavior.

CONCLUSIONS AND RECOMMENDATIONS

From these studies the following conclusions can be made:

1. Because of nonlinearities in vehicle response, the frequency response functions must be determined within the amplitude range that is expected to be encountered in normal highway operations.
2. From tests conducted on the JXS trailer it was determined that the pistons had a 2,000-lb friction level. After modifications, a new piston was mounted and tested and a friction level of 600 lb was ascertained. The shaking table proved effective in these determinations.
3. From data obtained during the tests conducted on the shaking table it can be concluded that levels of the dynamic component of the loads induced by the JXS at normal highway operations are within the same range of magnitude as those produced by the other trailers studied.
4. In most analyses, comparisons of trailer or truck performance are based on the number of repetitions to failure that can be applied to a particular pavement section. According to this approach, the trailer equipped with a single axle would be recommended for yielding the maximum number of repetitions (N = 22.6 E + 6). However, the main purpose of a road is not to withstand repetitions but to provide the means by which a payload can be transported from point A to point B. Therefore, an alternative method for comparing trailers is to compute the amount of payload they could carry over the life of a pavement. This value can be computed by multiplying the number of passes the pavement can withstand by the total load carried with each pass.

By applying this currently adopted methodology it is clear that a JXS-14 is capable of carrying more load over the life of the pavement section considered than any other trailer studied. In fact, it could carry about twice that carried by a semitrailer equipped with a single axle.

5. It is apparent that the semitrailer equipped with the leaf-spring suspension induces the highest dynamic components of the loads [highest RPL, DLR(w) and generally higher $H[L_1/b](w)$] and also exhibits the worst load distribution characteristics.

Both air bag suspensions exhibit a similar overall dynamic behavior. Whereas the RPL value for the tridem was worse than that of the tandem, the DLR(w) and the $H[L1/b](w)$ of the tridem were generally better than those of the tandem.

The relative difference of values suggests that the difference of performance between trailers equipped with leaf-spring suspensions and trailers equipped with air bag suspensions is greater than the difference between tridem trailers and tandem trailers equipped with air bags. From a dynamic point of view the effect of suspension type appears to be more significant than the number of axles.

6. A road test, despite its limited scope, indicated that the JXS operated at velocities of up to 60 mph with a maximum recorded vertical acceleration on the counter weight, over a rough portland cement concrete pavement section, of 0.15 *g* at a predominant frequency of 9 Hz. This value is expected to improve if the friction is significantly reduced in all pistons.

These conclusions enhanced the need of discussion and research in the following areas:

1. The determination of the frequency response function of trailers and trucks appears to be an effective tool for predicting trailer behavior. Tests should be conducted with a frequency sweep of at least a 0.1-Hz interval and with amplitudes varying within the range of values expected from highway operations. Road roughness data should be collected to make this possible.

2. On-the-road comparisons of the behavior of trucks and trailers should be made over pavement sections with various levels of roughness. Such tests should be performed to identify levels of roughness above which excessive damage is caused by the dynamic component of the loads. Furthermore "typical" sections of highway should be identified and surveyed to provide data for theoretical comparisons of trailers, suspensions, and axle configuration.

3. Further studies should be conducted to compare measured behavior (from item 2) to model predictions of stresses, strains, and deflections on pavements. A highly reliable model should be useful to evaluate new suspensions, load limits, and tire/axle configurations on pavements.

4. Use of the concept of "pounds carried per pavement life" could have major implications in the design, size, and characteristics of trucks and trailers and in the trucking industry overall.

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