Field Response And Dynamic Modeling Of An Asphalt Concrete Pavement Section Under Moving Heavy Trucks

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ABSTRACT

An asphalt concrete section on a test track in the PACCAR Technical Center in Mount Vernon, Washington, was instrumented with strain gauges at the surface and in pavement cores, and tested using a Falling Weight Deflectometer (FWD) as well as trucks at different speeds and tire pressures. This paper presents results from the analysis of the field tests, including comparisons with theoretical predictions using SAPSI, a computer program for the dynamic analysis of asphalt concrete pavements by the linear visco-elastic layer theory and the finite element method. The results indicate that static analysis using statically back-calculated layer moduli seems to be sufficient in analyzing FWD field tests, despite the fact that static back-calculation using FWD (dynamic) deflections will lead to "stiffened" elastic properties. Ninety percent of the measured strains in October 1991 and all measured strains in June 1992 were within ± 10 percent of their calculated values, versus 70 percent within ± 20 percent error in February 1993. The September 28-29 1993 truck tests showed a significant effect of truck speed as well as tire pressure on the asphalt concrete pavement response; the peak longitudinal strain in the asphalt concrete layer decreased by as much as 40% when the speed of the vehicle increased from idle to 40 mph. The same decrease occurred when the tire pressure was reduced from 90 psi to 30 psi. The SAPSI computer program did not predict the pavement's response to moving loads as well as predicting the response to stationary dynamic FWD loads: It predicts a decrease in strain amplitude of about 20 to 25% when the speed increases from idle to 40 mph. The September 30 1993 truck tests seem to support the spatial repeatability theory of pavement damage. The response of the pavement to six different truck and trailer combinations including different axle suspensions had the same troughs and peaks as a result of imposing the same roughness feature (a ramp) to excite the trucks.

INTRODUCTION

Collaboration between the University of Washington, the University of California-Berkeley, PACCAR Inc., and the California and Washington State Departments of Transportation led to instrumenting a full-scale asphalt concrete pavement test section located at the PACCAR Technical Center in Mount Vernon, Washington. The instrumentation consisted of strain gauges at the surface as well as in pavement cores. The tests included both Falling-Weight Deflectometer (FWD) as well as a series of full-scale truck tests. The computer program EVERCALC was used to backcalculate the pavement layer moduli, while the program SAPSI was used to predict the dynamic response of the pavement.

The objectives of the research were (i) to investigate the effects of different truck parameters on pavement response, including truck speed, tire/axle combinations, axle loads, and tire pressures, and (ii) to test the accuracy of the computer program SAPSI, by comparing theoretical deflections and strains with measured data from FWD as well as full-scale truck tests.

PACCAR TEST SITE

The test section is part of a durability track located at the PACCAR Technical Center in Mount Vernon, Washington (about 60 miles north of Seattle). The track is 1.5 mile long and is made of concrete with the exception of a 300 ft. asphaltic section in the center of one straight section. The instrumented section is approximately 14 feet wide and 40 feet long. It is closed to vehicular traffic except during scheduled pavement testing. The pavement cross-section consists of a 5.4 inch surface layer of dense graded asphalt concrete over a 13.0 inch crushed stone base. The subgrade is a sandy clay. The water table was measured at a depth of 66 inches during installation of the instrumentation. The test pavement was constructed using routine materials and construction practices.

BACKCALCULATION OF LAYER MODULI

The elastic moduli for each of the layers in the pavement structure were obtained by backcalculation using deflection data from WSDOT's Dynatest 8000 FWD. Testing was done in 61 locations totaling 130 drops with more tests on the five instrumented cores. The computer program EVERCALC was used for backcalculation of layer moduli. The applied FWD loads varied from 4,874 to 17,880 pounds and sensor spacings were set at 0, 8, 12, 24, 36, and 48 inches. The measured average mid-depth temperature of the AC layer during testing was 68°F in October 1991, 71°F in June 1992 and 45° F in February 1993. Layer thicknesses were obtained by coring. In addition, there was evidence that suggested that the subgrade soil was saturated at a relatively shallow depth. The shallow water table translates into the saturated subgrade soil behaving as a "stiff" layer. EVERCALC was used to back-calculate an appropriate value for the stiff layer modulus as well as to calculate the depth to the stiff layer. The approach consisted of varying the value of the stiff layer modulus from 10 ksi to 1,000 ksi and choosing the value which gave the lowest root mean square (RMS) value and the most reasonable AC modulus value. A stiff layer modulus of 40 ksi was obtained from the convergence procedure for the October 1991 and June 1992 tests. The stiff layer modulus was set at 50 ksi for the February 1993 tests. Because of the inability to physically measure the epoxy thicknesses, "effective" thicknesses were determined by varying the thickness of the epoxy on top and below each core until the theoretical strains (calculated by CHEVPC) matched the measured strains. The details of all of the above calculations are presented in Reference (1). Table 1 shows the effective layer thicknesses, and Table 2 shows the mean back-calculated layer moduli. The modulus of the epoxy was estimated to be about 500,000 psi.

Table 1. Effective pavement layer thicknesses (inches)

	AXIAL CORE			
LAYER	1	3	4	5
Epoxy	0.4	0.25	0.0	0.6
AC	4.9	4.9	4.9	4.9
Epoxy	0.4	1.25	0.5	0.6
Base	12.7	12.0	13.0	12.3
Subgrade (Oct'91)	42.7	46.0	46.1	43.8
Subgrade (Feb'93)	57.1	60.4	60.5	58.4
Stiff Layer	semi-infinite	semi-infinite	semi-infinite	semi-infinite

INSTRUMENTATION

A foil-gauge type of strain gauge was used to measure the various strain responses. An Australian-made Multi-depth Deflectometer (MDD) with four linear variable differential transformers (LVDTs) was installed to measure pavement layer deflections. For temperature data, a multi-sensor temperature probe was used. A total of 102 strain gauges and one MDD were installed in the pavement section. Twenty gauges were installed in five axial cores to measure longitudinal and transverse strains at the top and bottom surfaces of the AC layer; forty shear strain gauges were mounted on ten cores and a long transverse slot extending from the centerline to the shoulder of the pavement; and forty two (longitudinal and transverse) surface gauges were placed along the wheel path at about one foot intervals. All gauges were installed by cutting/coring the existing pavement since no new construction was performed for the purpose of conducting the tests. The physical layout of the gauges at the test section is shown in Figure 1. The layout was designed to ensure the collection of critical pavement responses for both layer elastic and finite element analysis methods. The movement of the truck proceeded in order of increasing gauge number, or from left to right on Figure 1, with the left hand side wheels contacting the gauges. The axial cores were displaced laterally to allow collection of strain measurements from both wheel paths and the approximate centerline of the wheel base. The longitudinally oriented surface gauges were specifically designed to evaluate the dynamic response of a truck as it travels down the pavement section. The analysis presented herein involves only the axial core gauges and the surfaces gauges along the wheel path (62 out of the 102 installed gauges.) The response of the shear gauges was not analyzed. Furthermore, it was not possible to obtain data from the multi-depth deflectometer.

Two types of epoxy were used: On type *(Micro Measurement M-Bond AE-10)* was used to glue the gauges to the pavement, and the second type *(Sikadur® 32 Hi Mod 2)* was used to bond cores to the pavement or to fill the voids in the cut.

Table 2. Pavement layer properties

LAYER	ELASTIC MODULUS			POISSON RATIO
	October 1991	February 1993		
	All cores	Core 1	Cores 3, 4 & 5	
Epoxy	500,000	500,000	500,000	0.35
AC	562,800	1,575,700	1,510,000	0.35
Base	14,800	20,300	27,500	0.40
Subgrade	10,200	10,700	13,400	0.45
Stiff Layer	40,000	50,000	50,000	0.35

ANALYSIS OF STRAIN DATA FROM FWD TESTS

The analysis of FWD strain data was limited to Cores 1, 3, 4 and 5 because of better accuracy in the pavement thickness data and because they are instrumented with strain gauges at the bottom of the asphalt concrete layer.

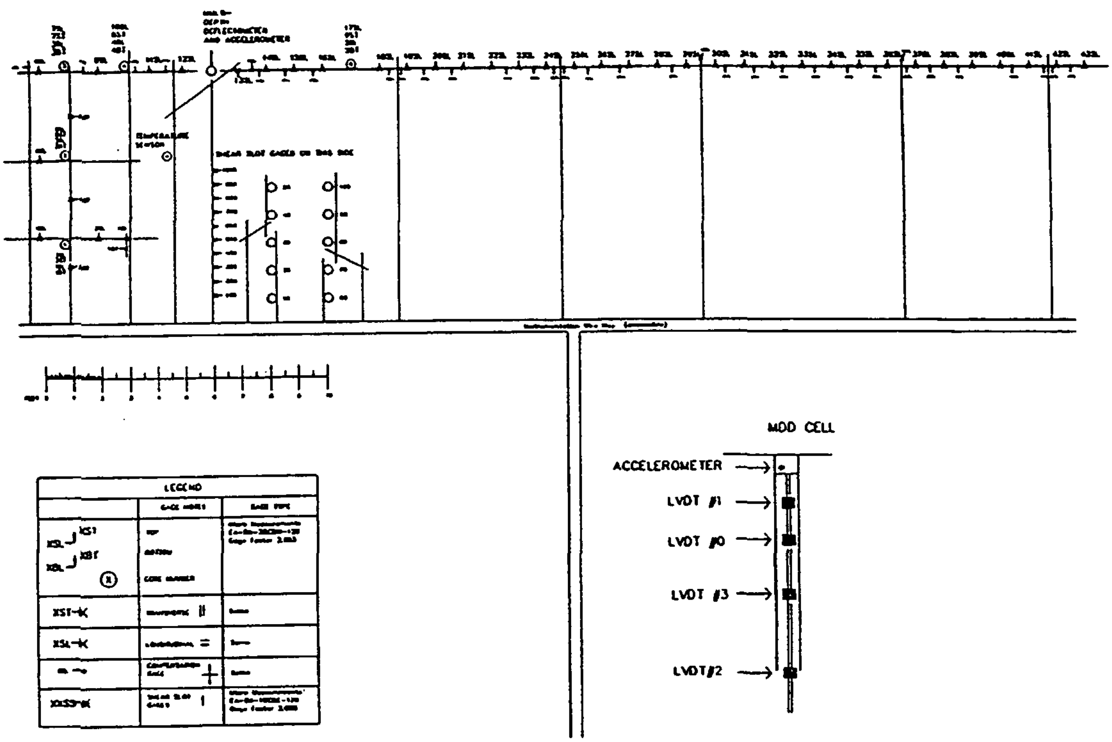


Figure 1. Instrumentation layout

DYNAMIC AC PROPERTIES

Two sets of profiles were used in the analysis: One set with the properties of the asphalt concrete layer held constant with frequency and a second set where the AC properties were varied with frequency. The reason for using frequency-dependent AC properties stems from the fact that asphalt is a visco-elastic material and its properties (modulus, damping ratio and Poisson's ratio) have been shown to be strongly frequency-dependent (2). In the frequency-independent profiles, the value for the AC modulus is the one back-calculated from FWD deflection data. In the frequency-dependent profiles, the curves for the AC properties were developed using a similar procedure to the one reported by Siddhartan etal (3). In this procedure, the curves reported by Sousa (2) are used to describe the variation with frequency of the dynamic Young and shear moduli ($|E^*|$ and $|G^*|$) as well as the damping ratio of the AC layer (see Figure 2 (a) and (b)). The intercept for $|E^*|$ is obtained by iteration until the peak transient strain due to a unit FWD pulse is equal to the static strain which corresponds to the backcalculated AC modulus, EQ(1).

$$\varepsilon = \max \sum_{s=0}^{N/2} \frac{p_s}{|E^*_s|} = \frac{1}{E_{FWD}}$$

where: p_s = *Fourier transform of the load* (1)

s = *Frequency number.*

Convergence was reached for $|E_0^*| = 273{,}500$ psi. The initial Poisson's ratio was obtained from the measured initial values of $|E^*|$ and $|G^*|$, as reported by Sousa, using elasticity. The computed value was 0.537 which is close but exceeds the maximum allowable value in elasticity of 0.5. Therefore a value of 0.499 was assumed. The initial shear modulus, $|G_0^*|$, was then computed from elasticity. The variation with frequency of Poisson's ratio was made to fit the observed trends in $|E^*|$ and $|G^*|$. Figure 2 (c) and (d) shows the final curves used for the moduli and Poisson's ratio respectively. To check the validity of the procedure the profile was subjected to the FWD pulse, and the tensile strain at the bottom of the AC layer was compared with the measured value. The agreement was excellent: 133 microstrains versus 130 measured.

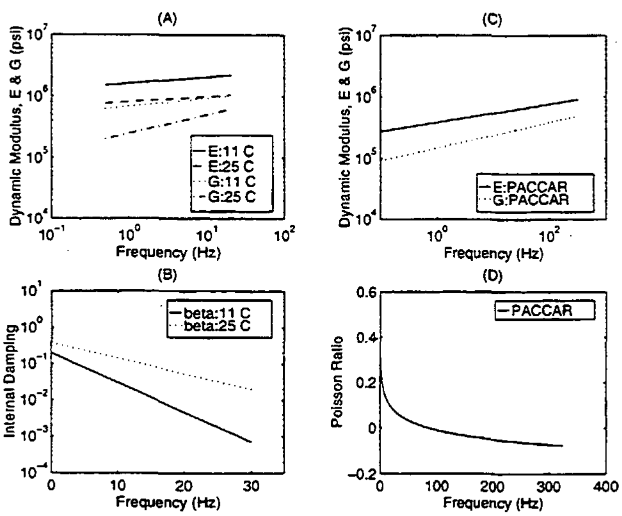


Figure 2. Asphalt concrete properties versus frequency

PREDICTION OF STRAINS USING SAPSI

The FWD load was modeled as a haversine pulse with a duration of 30 milli seconds. Using effective layer thicknesses for Axial Cores 1, 3, 4 and 5, and back-calculated layer properties, theoretical transient strains were calculated by SAPSI (4). Comparisons of measured strains with calculated static strains from CHEVRON and dynamic strains from SAPSI for all three test series are shown in Figures 3 through 5.

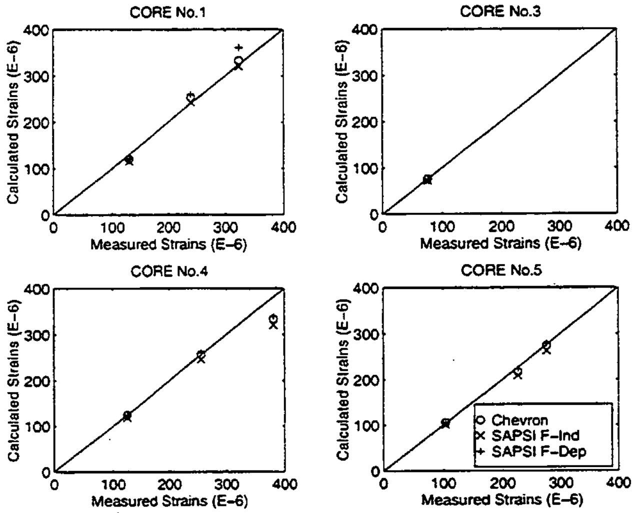


Figure 3. Predicted vs. measured strains-Oct.'91 FWD tests

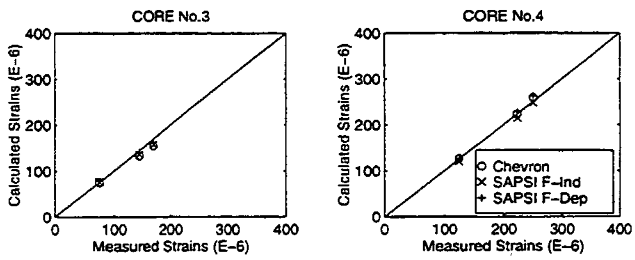


Figure 4. Predicted vs. measured strains-June'92 FWD tests

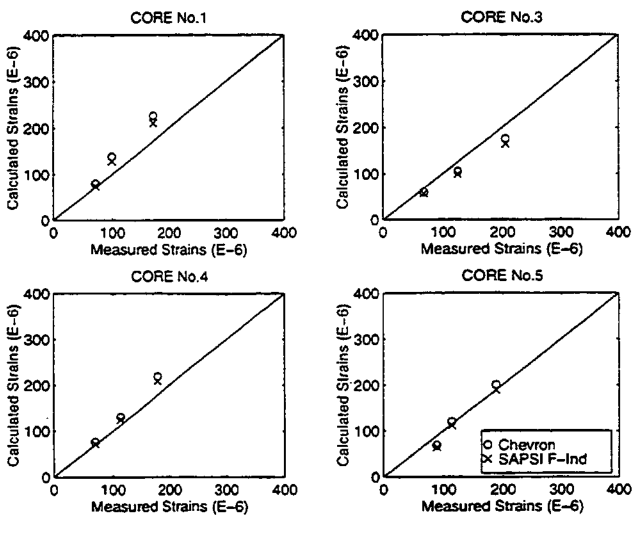


Figure 5. Predicted vs. measured strains-Feb.'93 FWD tests

Very good agreement exists between measured and predicted strains. Ninety percent of measured longitudinal strains in October 1991 tests and all measured strains in June 1992 tests are within +/- 10 percent of their calculated values. Only About 70 percent of the measured strains in February 1993 tests are with in +/- 20 percent of their calculated values. This could be due to measurement errors. As time passes after the initial installation of strain gauges and the refitting of the cores into the pavement section, exposure to moisture and temperature fluctuations in the pavement causes the sensitivity and reliability of the strain gauges to decrease.

These results constitute a good field verification for both CHEVPC's closed-form solution and SAPSI's finite element formulation. The results also imply that static analysis of pavements using statically back-calculated layer moduli seems to be sufficient for accurately predicting the pavement's field response under stationary dynamic FWD pulse loads.

SEPTEMBER 28-29 TRUCK TESTS

The first series of full-scale truck tests was conducted on September 28 and 29, 1993. The tests were used in the analysis for investigating the effects of truck speed, tire pressure, and pavement temperature on pavement response as well as investigating the use of the computer program SAPSI for predicting pavement response under moving loads.

TEST PROCEDURE

The truck used for the 'pressure/speed' tests was a Peterbilt 359 truck with a load frame and instrumented axles to calculate tire forces. The elevation views of this truck and the other test vehicles are shown in Figure 6.

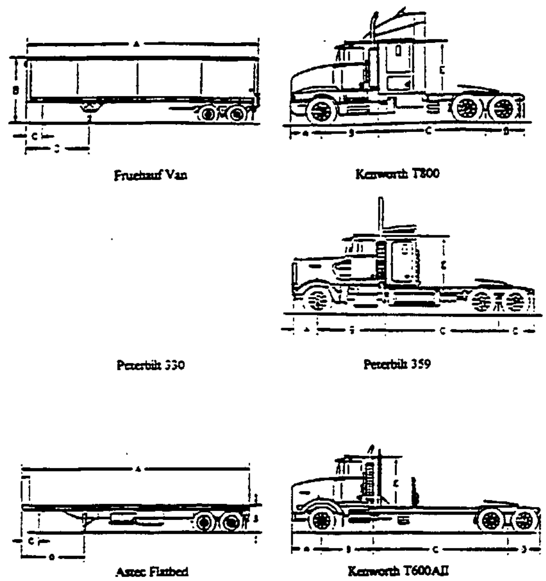


Figure 6. Elevation views of test vehicles

Testing was conducted in three blocks: Mid-morning of September 28; afternoon of September 28; and mid-morning of September 29. Each test block consisted of three sets of tests corresponding to three different tire pressures: 90 psi, 58 psi and 31 psi. The maximum safe speed for testing on this track section was 45 mph; so for each tire pressure, three truck speeds were used: Creep speed (1.7 mph,) 20 mph and 40 mph. The tests were conducted in triplicates and according to a random order.

Because some preliminary results from earlier tests showed the effect of lateral offset to be very significant, special care was taken in marking the pavement and reading the tire imprint. Lime dust was used to show the tire imprint. If the offset was greater than 4 inches the test was repeated.

LOAD MEASUREMENTS

Measured loads were used to investigate the variability of tire loads with runs of equal truck speed and tire pressure and to study the effects of speed and pressure on tire loads. Measurements indicated that the variability is within 5 percent for a given speed and tire pressure, and that the effects of truck speed and tire pressure, respectively, on the load are insignificant. Accordingly, it was concluded that there was no need for correcting the measured response for the level of load applied and that the measured static loads could be used as the peaks of the load pulses in the portion of the analysis where SAPSI was used to predict the pavement's response.

STRAIN MEASUREMENTS

Strain measurements were used to investigate the effects of truck speed and tire pressure on pavement response. Figure 7 shows typical time histories of measured strains in the AC layer.

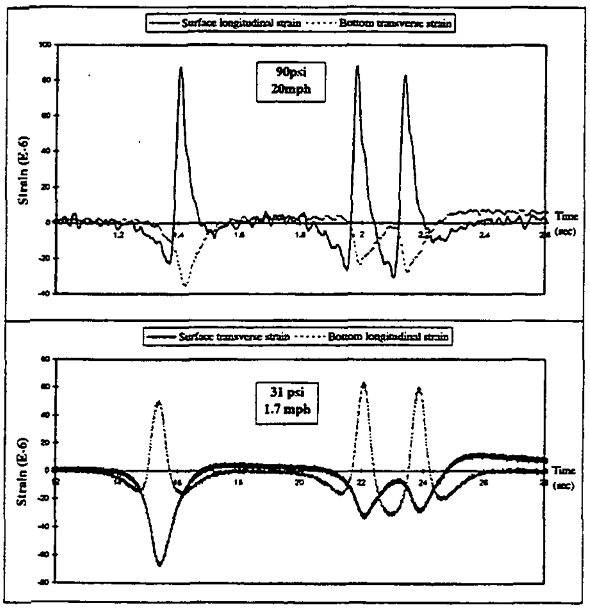


Figure 7. Typical measured strain time histories in AC layer

Within a subset of tests with constant tire pressure, the pavement's surface temperature did not vary much; this means that the temperature at the bottom of the asphalt concrete layer should be very close to a constant within each subset of tests. Accordingly, no temperature correction was used in analyzing the effect of truck speed for a given subset of tests with constant tire pressure, The effect of the offset between the applied loads and the recording strain gauge was accounted for using the computer program SAPSI by calculating the response of the pavement at different offsets along a transverse axis underneath each axle, due to multiple applied loads with the Peterbilt 359 tire geometric configuration. The experimental results were then normalized with respect to offset.

SPEED EFFECT

The effect of speed on longitudinal / transverse strains at the bottom / top of the asphalt concrete layer in the three different cores was investigated at the three different tire pressures. Figure 8 shows the mean values and the corresponding standard deviations from all tests and all axles for Core 3. Similar trends were observed for Cores 1 and 4. The strains due to all axles were included in the figure because the variation in measured strain with axle type for all tests was small (4).

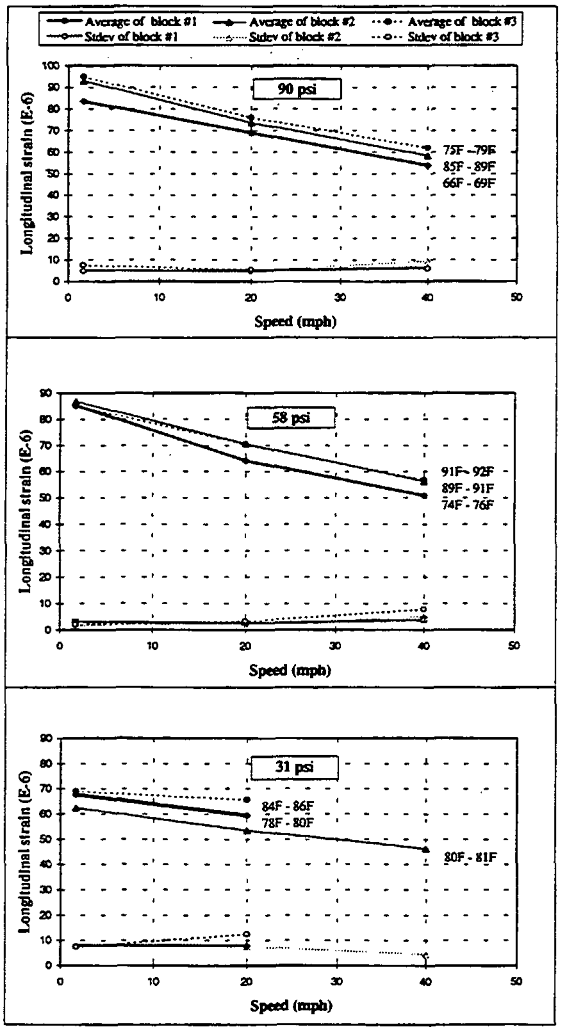


Figure 8 Longitudinal bottom strain in AC versus speed

The speed curves show that :

- Increasing truck speed from 0 to 40 mph reduced the longitudinal strain a the bottom of the asphalt concrete layer by about 25 to 40%.
- The rate of decrease due to the speed effect seems to decrease with increasing speed.
- The speed effect seems to decrease with decreasing tire pressure.

Figure 9 shows the effect of speed on transverse strains at the bottom of the asphalt concrete layer in Core 4.

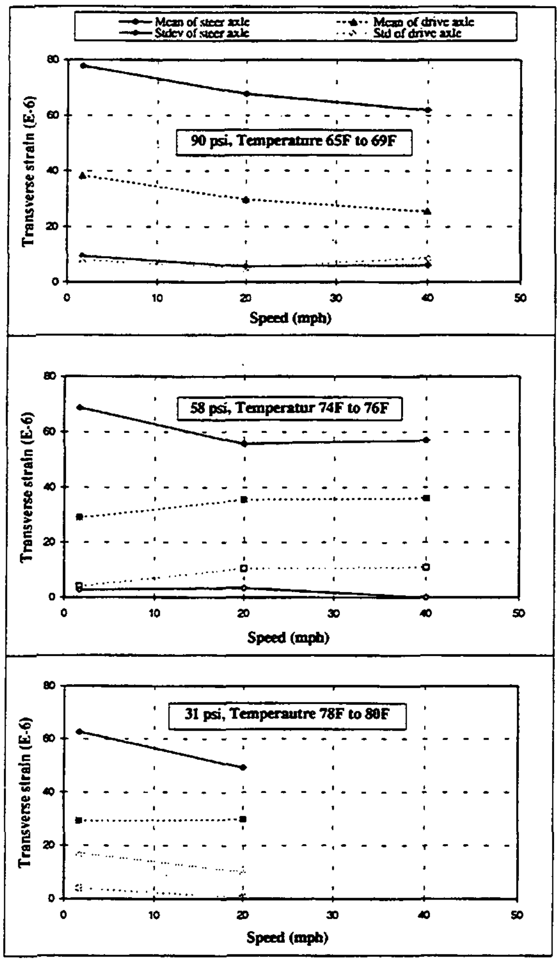


Figure 9. Transverse bottom strain in AC versus speed

The figure indicates that:

- The speed effect for transverse strains is less pronounced than for longitudinal strains.
- The transverse strain due to the drive axles is about half of the longitudinal value. This is due to the dual tires which generate offsetting strains in compression and tension respectively in the transverse direction. SAPSI results shown in Figure 10 clearly show the transverse strain due to the drive axle to be significantly lower than the longitudinal strain and the strain due to the steer.

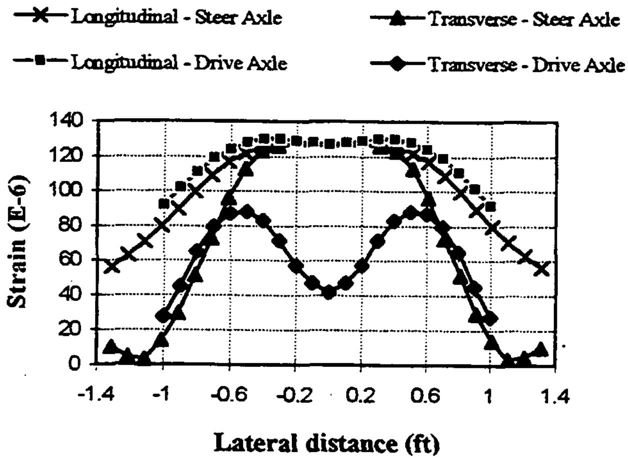


Figure 10. Typical lateral distributions of strain

Figure 11 shows the effect of speed on surface longitudinal strains for Core 4.

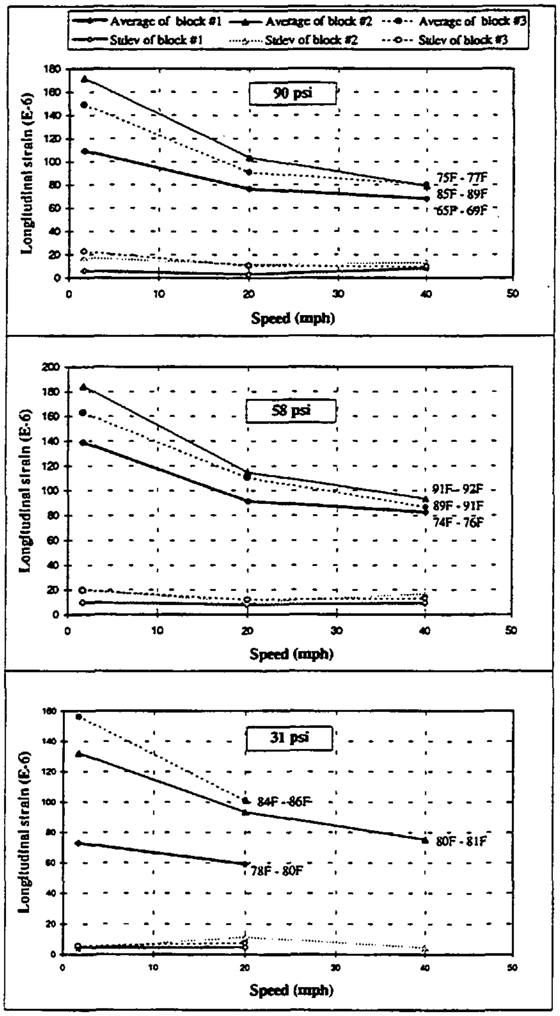


Figure 11. Longitudinal surface strain in AC versus speed

The figure shows that:

- The speed effect is more pronounced at the surface than at the bottom of the asphalt concrete pavement layer. Increasing truck speed from 0 to 40 mph reduced the longitudinal strain a the top of the asphalt concrete layer by about 38 to 64%.
- The surface strain is higher than the bottom strain. This is due to the pavement temperature which is higher at the surface than at the bottom.

TIRE PRESSURE EFFECT

Because the time periods between test blocks at different tire pressures were long enough to cause significant variations in pavement temperature, the effect of temperature on pavement strain needed to be compensated for.

To do this, the data were lumped into measurements which correspond to a constant truck speed and a constant tire pressure and then plotted as a function of the pavement surface temperature. A linear relationship between the strains at two different temperatures was developed for each case. Using these lines, strains at a constant temperature (T = 80 °F), was calculated. For the case of low pressure and low speed (p = 31 psi and v = 1.7 mph) the average of all the strains (corresponding to each axle type) was taken, since the temperature was almost constant (4). Therefore, for a constant temperature of 80°F the effect of tire pressure was studied at the three speeds.

Figure 12 shows the effect of tire pressure on longitudinal strain at the bottom of the asphalt concrete layer for Core 1. The results shown in the figure and those of Cores 3 and 4 (4) indicate that:

- Decreasing tire pressure from 90 psi to 31 psi reduced the longitudinal strain at the bottom of the asphalt concrete layer by about 25% to 40%.
- The pressure effect is somewhat reduced at higher speeds.

SPATIAL REPEATABILITY TESTS

The last series of full-scale truck tests at PACCAR's Technical Center was conducted on September 30, 1993. The primary goal of these tests was to investigate the theory of "spatial repeatability" in pavement damage. This concept states that for any given truck speed, the wheel load time histories generated by a particular heavy vehicle are repeated closely on successive passes over a given stretch of road. Since all heavy commercial vehicles have approximately the same natural frequencies and are driven at approximately the same speed on highways, then for a given pavement the dynamic wheel load peaks would always occur within a relatively narrow band of road sections (5). Accordingly some portions of the road may incur much larger damage than other portions. This experiment attempts to study this phenomenon using controlled real-scale tests.

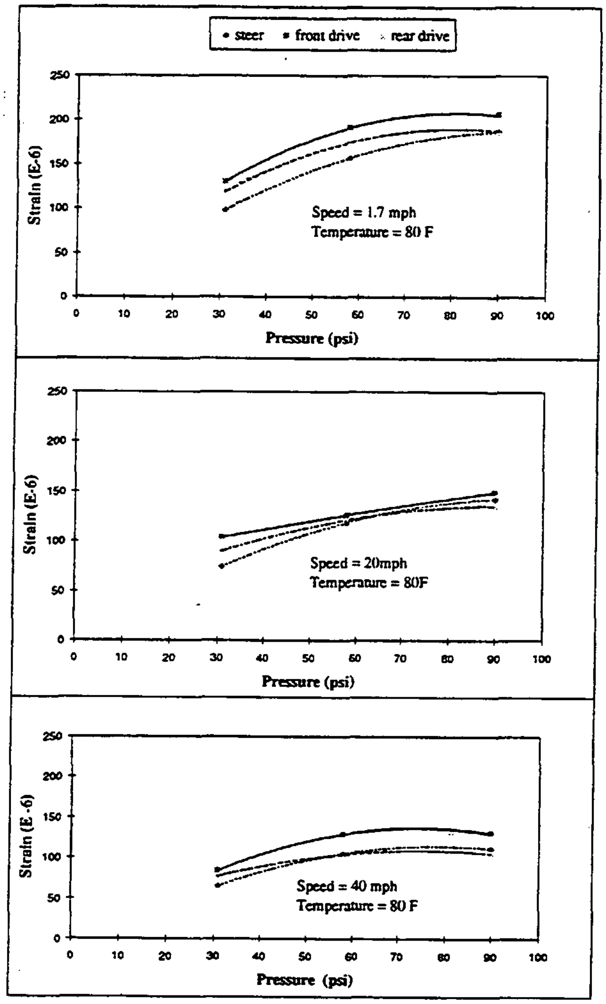


Figure 12. Bottom longitudinal strain in AC vs. pressure

TEST PROCEDURE

For these tests, a ramp was used to excite the different trucks. The ramp consisted of three portions: A 4 ft x 2 in section up, a 7 ft flat section and a 4 ft x 2 in section down. Four trucks and two trailers with different suspensions were used: Peterbilt 359 and 330 trucks, Kenworth T800 and T600, and a flat bed and van trailers. The Peterbilt 359 and 330 trucks as well as the trailers were equipped with leaf spring suspensions; the Kenworth T800 had a walking beam rear suspension; and the Kenworth T600 had air suspensions. None of the additional trucks and trailers was equipped with instrumented axles. Consequently, it was assumed that the repeatability of the trucks response for a given pavement roughness could be indirectly studied by examining the pavement response at closely spaced surface strain gauges along the test track. Figure 6 above shows the various test vehicles.

Testing was conducted in three blocks: Mid-morning; mid-afternoon; and late-afternoon of September 30, 1993. Each test block consisted of six sets of tests corresponding to different truck/trailer combinations. For all tests, the truck speed was 20 mph and the tire pressure was 90 psi. The tests were conducted in triplicates and the order of each set of triplicate tests was random. The three test blocks were identical except for the time-of-the-day and the order of triplicate test sets. The test procedure was exactly the same as in the September 28 and 29 tests. The bulk of the test results consisted of strain measurements from the surface gauges. Tire load measurements from the truck-mounted gauges on the Peterbilt 359 were also available. The three other trucks and the trailers were not instrumented. Figure 13 shows the measured axle load variations as a function of distance for triplicate runs at different truck speeds and for different axles over the "smooth" test track. The figure clearly shows a repetitive pattern on successive runs. This agrees with the theory of spatial repeatability.

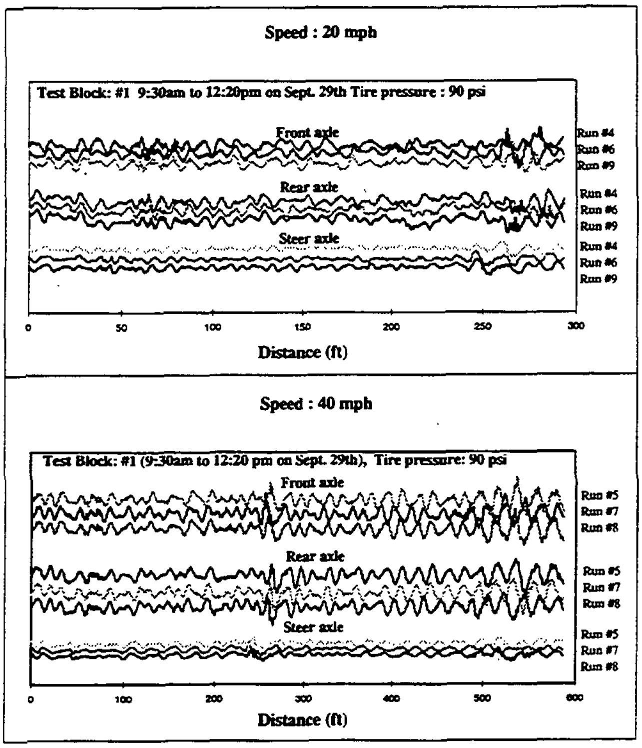


Figure 13. Spatial variation of axle load

STRAIN MEASUREMENTS

Surface strain measurements were used to investigate the concept of spatial repeatability in lieu of wheel loads since only the PB 359 truck was instrumented. This is an indirect way of assessing the repeatability of the loads since load and strain should be directly related. Strain values were corrected for offset and temperature effects using equations provided by Mahoney* based on layered elastic theory and laboratory measured AC moduli. Figure 14 shows the variation with distance of the mean and standard deviation of the surface strain for the six vehicles used in the testing, with the data grouped by axle and by vehicle, respectively. The figure shows very similar variations of high and low spots on the pavement from all trucks with a repetitive trend for all axles, thus supporting the theory of spatial repeatability. The PB 330 truck can be singled out from the figure as the most damaging truck to the pavement. The figure also indicates that the highest damage among axles is caused by the steer axle.

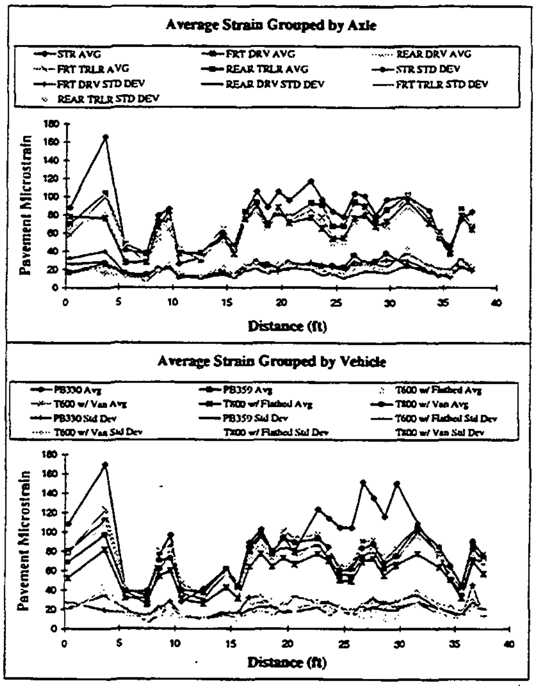


Figure 14. Spatial variation of peak strain

SAPSI ANALYSIS OF TRUCK TESTS

The computer program SAPSI was used to calculate the pavement response in the September 28 and 29 1993 series of truck tests. The purpose of the analysis is to evaluate SAPSI's capability of predicting the pavement's response to moving loads and to analytically investigate site effects on dynamic pavement response.

MODELING OF MOVING LOAD

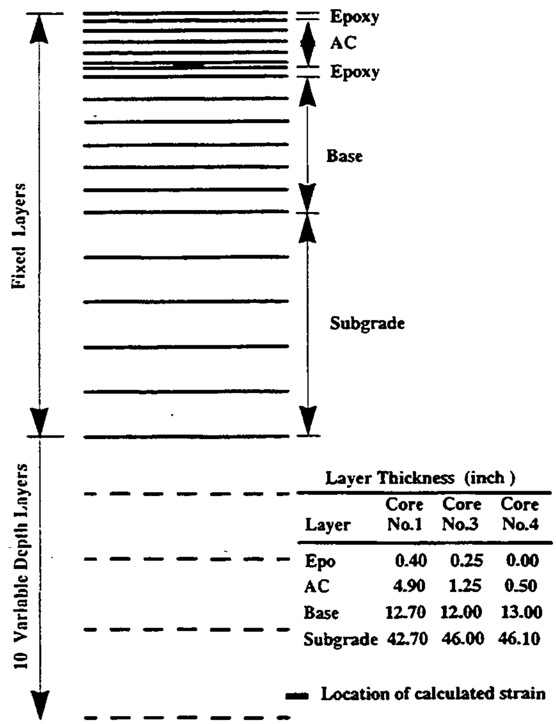
Since the solution in the SAPSI computer program is for stationary loads and cannot model a moving load truly, the moving load was modeled as a haversine pulse with its duration equal to the time required for the wheel to pass by the measurement location. Therefore the duration of the pulse is a function of truck speed and tire pressure. The transient analysis in SAPSI was done only for the case of a single steer wheel using a haversine pulse with different durations corresponding to the different tire pressures and truck speeds.

MODELING OF PAVEMENT CORES

The same profiles for October 1991 were used in the analysis of September 1993 truck tests because the weather conditions were nearly identical. Theoretical strains were calculated for Axial Cores 1, 3 and 4 using profiles with the back-calculated frequency-independent AC properties as well as with frequency-dependent properties, as described above. Figure 15 shows the modeling of the different cores. The temperature at the bottom of asphalt concrete layer was

* personal communication

assumed to fluctuate less than the surface temperature because of the thickness of asphalt concrete. The temperature was assumed to be uniform through the asphalt concrete and to be 68° F. Theoretical strains and deflections were calculated at the bottom of the asphalt concrete, not at the bottom of epoxy, because the strain gauges were glued to the asphalt concrete with epoxy which was then used to fill the voids in the core.



Layer	Core No.1	Core No.3	Core No.4
Epo	0.40	0.25	0.00
AC	4.90	1.25	0.50
Base	12.70	12.00	13.00
Subgrade	42.70	46.00	46.10

Layer Thickness (inch)

Figure 15. Pavement models used in SAPSI analysis

EFFECT OF TRUCK SPEED

SAPSI results using both frequency-dependent and frequency-independent AC layer properties were compared with field data. There was no measured data for the vertical deflection, thus no comparison between predicted and measured deflections was possible. The effect of truck speed on vertical deflection and longitudinal tensile strain at the bottom of the AC layer is shown in Figures 16 and 17 for Cores 1 and 3 respectively. These results correspond to the subset of tests from Block 1, conducted in mid-morning on September 29, 1993, with a tire pressure of 90 psi. The calculated strains using the frequency-independent profile show some amplification in the response near 20 mph, while the field data do not. These theoretical results can be explained by looking at the steady-state response from both profiles, as shown in Figure 18. The figure clearly shows an amplification in the response at lower frequencies (30-40 Hz) in the case of using frequency-independent AC layer properties. This frequency range matches the frequency content of a 20 mph load pulse. Since the frequency content of a 1.7 mph load pulse is near zero frequency (creep speed) and that of a 40 mph load pulse extends beyond the range for 20 mph, the strain at 20 mph will be higher than at 1.7 mph and 40 mph respectively.

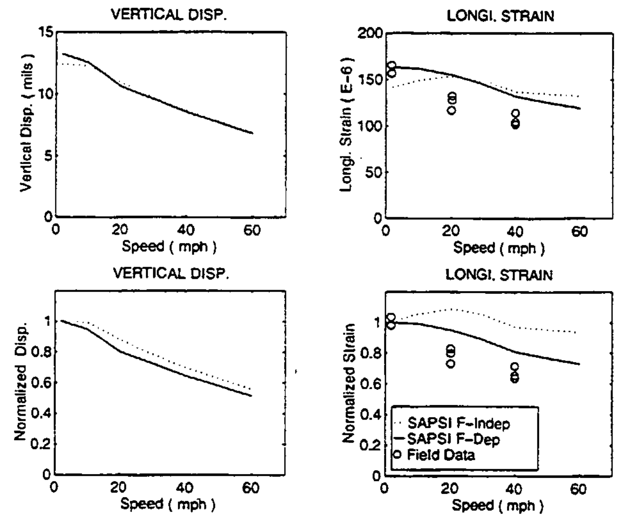


Figure 16. Effect of speed on pavement response - Core 1

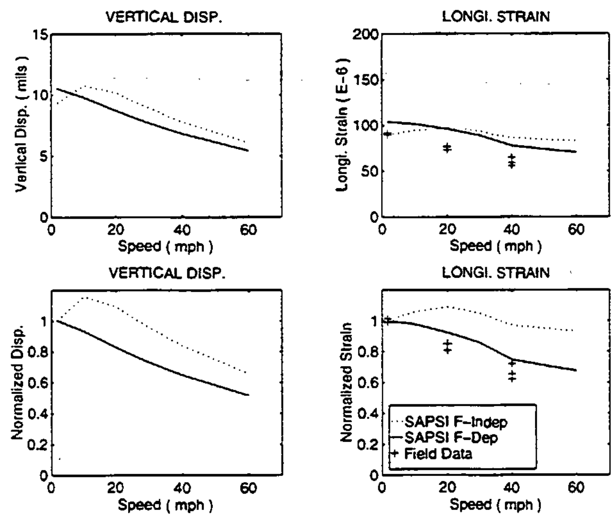


Figure 17. Effect of speed on pavement response - Core 3

The calculated strains using the frequency-dependent profile, on the other hand, show a consistent decrease as the truck speed increases. Increasing the speed from creep to 60 mph causes the strain to decrease by about 28%, 32% and 35% at Cores 1, 3 and 4 respectively. The decrease in strain amplitude is 20%, 26% and 22% when the speed increases from creep speed to 40 mph. This decrease is somewhat smaller than observed in the field. Nonetheless, SAPSI's predictions show a very good trend and the results are within 20% for Cores 1 and 3. The predictions for Core 4 are up to 50% off (4).

The above analysis shows that the results using frequency-dependent AC layer properties are closer to the field measured values, both in absolute value and in trend, than those using frequency-independent properties. This is an indirect field verification of the laboratory testing results

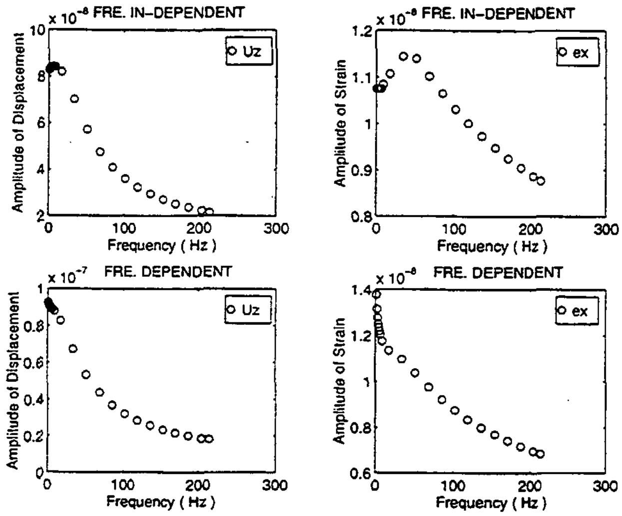


Figure 18. Steady-state response of different profiles

obtained by Sousa (2) and others indicating that the asphalt concrete properties are strongly dependent on the frequency of loading.

SAPSI's computations did not show as good of an agreement with field measurements from truck tests as in FWD tests since modeling a moving truck load as a stationary pulse is not an exact representation: When modeling the moving truck load as a stationary haversine pulse, the load/pressure exerted by the tire is applied only when the tire is in direct contact with the measurement point in the pavement. This means that when the truck's wheel does not touch the measurement point it does not contribute any effect to the response of measurement point in the pavement. In reality, the wheel load sends stress waves as it approaches the measurement point, and theses waves (in the form of body and surface waves) propagate so that the effect of the approaching wheel load is felt by the fixed measurement point in the pavement before and after the load is directly on top of the point. These waves could be a combination of direct waves from the moving load and reflected waves from a layer boundary below the surface such that the net pavement response may be amplified or de-amplified, depending on radiation damping, relative to the stationary response. Thus, in general, a moving truck load cannot be modeled exactly by a stationary transient haversine pulse, although it may be a reasonable approximation. The results from SAPSI's stationary load analysis seems to indicate that modeling a moving truck load as a fixed pulse is not enough to account for these interactions between traveling stress waves, i.e. handle a moving truck, although the predictions are not too unreasonable. Because of this, there is an on-going research study at Michigan State University aimed at improving the solution in SAPSI to make it able to predict the response of pavements to truly moving loads.

The theoretical calculations indicate that the speed effect is more pronounced in the vertical deflection than in the tensile strain at the bottom of the asphalt concrete layer. The vertical deflection decreases by about 45% for all cores, as the speed increases from creep to 60 mph, when using frequency-dependent AC properties. The deflection results using frequency-independent AC properties are very close to those using frequency-dependent properties for Core 1. Cores 3 and 4 results using frequency-independent AC properties show some amplification at about 10 mph, then the trend becomes very close to the one using frequency-dependent AC properties. The net decrease in vertical deflection is about 45% for Core 1 and about 30% for Cores 3 and 4 when the truck speed increases from creep speed to 60 mph.

TIRE PRESSURE EFFECT

Figure 19 shows the effect of tire pressure on vertical deflection and longitudinal strain at the bottom of AC at different truck speeds for Core 1. The figure represents the results of SAPSI calculations at 68 °F with frequency-dependent AC properties and field data (adjusted to 68 °F) for each of the three cores. Temperature adjustment was done using the measured data for the same core, and at the same tire pressure and truck speed. The adjustment required that the data be extrapolated because all but nine runs (September 29, 90 psi tests) were at temperatures higher than 68 °F. There was no field data for vertical deflections and for strains at 31 psi. The applied loads are the same in all cases so that the difference in tire pressure translates to a difference in tire contact area.

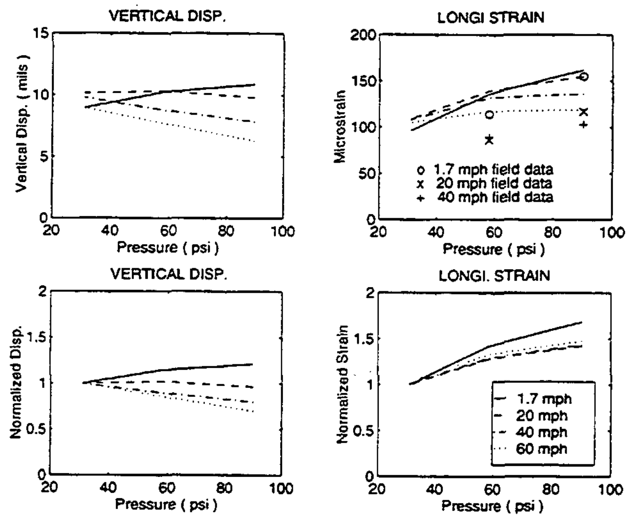


Figure 19. Effect of pressure on pavement response

The figure shows that both measured and calculated longitudinal strains at the bottom of the AC layer increase as the tire pressure increases, at all truck speeds. This is due to larger tire contact areas at lower tire pressures. The rate of increase is highest at creep speed. Comparison of measured to predicted strain values indicated that the best results are for Core 3, then Core 1, with Core 4 exhibiting the worst results. Agreement was best at creep speed with an error within 10% for Core 3 and within 15% for Core 1. At higher speeds, the error was within 15 to 20% for Core 3 and within 35 to 40% for Core 1 (4).

Figure 19 indicates that the vertical deflection calculated by SAPSI increases as the tire pressure increases at low speed, but it decreases at higher speed values. This can also be explained by the variation in the tire contact area. At very low speed, the higher the pressure, the sharper the deflection basin and the higher the deflection. However, as the speed increases, the duration of the pulse load shrinks considerably, and becomes more significant than the variation due to the decrease in the tire contact length.

EFFECT OF DEPTH TO STIFF LAYER

To investigate the effect of the depth to stiff layer on the vertical deflection and longitudinal strain, the thickness of subgrade was varied from 2 ft to 20 ft. The profile used was that of Core 1. Transient analysis in SAPSI was performed at the three speeds, 1.7 mph, 20 mph and 40 mph, and using frequency-independent as well as frequency-dependent profiles. Figure 20 shows the results of the analysis. The figure indicates that the tensile strain at the bottom of the asphalt concrete layer is independent of the depth of the stiff layer for all three speeds and for both frequency-dependent and frequency-independent profiles. The vertical deflection is affected by the depth of the stiff layer only at very low speed, with the deflection decreasing with decreasing depth to stiff layer. This is expected since at very low speed, the behavior approaches static conditions where the shallower the stiff layer the stiffer the foundation soils get and the lower the vertical deflection becomes. Note that for the PACCAR site the depth to stiff layer is about 5 feet.

CONCLUSIONS

The present study has led to the following conclusions:

From the results of FWD tests:

- Ninety percent of the measured strains in October 1991 FWD tests and all measured strains in June 1992 FWD tests were within +/- 10 percent of their calculated values, using both static and dynamic analyses. Seventy percent of the measured strains in February 1993 were within +/- 20 percent. These results constitute a very good field verification of the SAPSI computer program.
- Static analysis using statically back-calculated layer moduli seems to be sufficient in analyzing FWD field tests, despite the fact that static back-calculation using FWD (dynamic) deflections will lead to "stiffened" elastic properties.
-

From the results of 28-29 September 1993 truck tests:

- The effect of truck speed on the response of asphalt concrete pavements is significant. Increasing truck speed form 0 to 40 mph reduced the peak tensile strain in the asphalt concrete by about 25 to 40 percent.
- The effect of tire pressure on the response of asphalt concrete pavements is significant. Decreasing the tire pressure from 90 to 30 psi reduced the tensile strain in the asphalt concrete layer by about 25 to 40 percent.
- The speed effect is somewhat reduced at lower pressures.

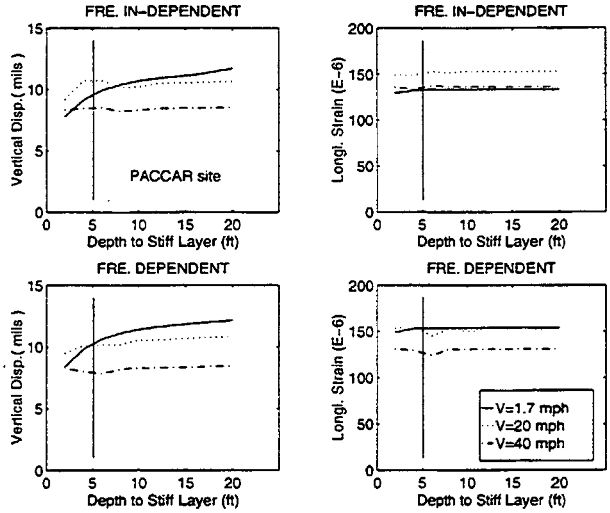


Figure 20. Effect of depth to stiff layer on response

- The pressure effect is somewhat reduced at higher speeds.

From the spatial repeatability truck tests:

- The different truck-trailer combinations with different axle suspensions when excited by the same ramp caused a similar response in the pavement, thus supporting the spatial repeatability theory of pavement damage.
- The steer axle, among all axles, caused the highest peak strains in the pavement.
- The PB 330 truck with single axles and leaf-spring suspensions, among all truck-trailer combinations, caused the highest peak strains in the pavement.

From the SAPSI analysis of truck tests:

- Agreement between SAPSI's predictions and field measurements was not as good in the truck tests as in the FWD tests. This is because the current solution in SAPSI assumes a stationary load. An on-going study is aimed at improving the solution in SAPSI to make it able to handle moving loads.
- The analytically-predicted tensile strains in the asphalt concrete layer using frequency-dependent properties for the asphalt concrete were closer to the field measured values, both in absolute value and in trend, than those using frequency-independent AC properties. This is an indirect field verification of the strong dependency of asphalt concrete properties on the frequency of loading and an indication that the speed effect on tensile strain is largely due to the frequency-dependent visco-elastic properties of asphalt concrete.
- Speed has a more pronounced effect on vertical deflection than on tensile strain in the AC layer, as shown by theoretical SAPSI predictions.
- SAPSI's prediction of the tire pressure effect on the tensile strain at the bottom of the AC layer was within 10 to 15% of field measurement at creep speed,

exhibiting an increase in the tensile strain of about 50% when increasing the tire pressure from 30 to 90 psi.

- Tire pressure has a less pronounced effect on vertical deflection than on tensile strain in the AC layer. The analytical results show about 10 to 15% increase in vertical deflection when increasing the tire pressure from 30 to 90 psi at creep speed, as compared to 50% for the tensile strain. At higher speeds, the effect of increasing tire pressure is to *decrease* the pavement's vertical deflection by as much as 25% at 60 mph.
- The analytical results from SAPSI indicate that the tensile strain at the bottom of the asphalt concrete layer is not affected by the depth of the stiff layer for all three speeds (1.7, 20 and 40 mph) and for both frequency-dependent and frequency-independent profiles. The vertical deflection is affected by the depth of the stiff layer only at very low speed, with the deflection decreasing with decreasing depth to stiff layer.

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