

Experimental Determination of Pressure Distribution of Truck Tire-Pavement Contact

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ABSTRACT

The results are presented of an experimental determination of pressure distributions beneath statically loaded truck tires using a pressure-sensitive film. A load frame fitted with a hydraulic ram was used to statically load a bald and treated 10-20 bias ply truck tire. The use of pressure-sensitive film allowed the net contact area--as well as the entire pressure distribution--to be captured, and the data to be stored by using an automated print reading system. The results indicate that the treaded tire produced the highest pressures in the tire shoulder region for the cases studied, except for the overinflated case. High inflation pressures caused the peak pressures to move from the tire shoulder toward the tire centerline. The results also indicate that heavy axle loads produced regions of high pressure in the tire shoulder region. Experiments conducted on bald tires show similar trends; however, the overall pressure distribution is more continuous because of the lack of treads.

One of the major costs incurred by highway departments in the United States is maintaining public roads in a serviceable condition. A variety of factors are known to contribute to pavement damage, including climate, traffic density, and the loads from automobile and truck tires. Historically, the subject of contact pressure distribution between a tire and pavement has received little attention for several reasons, including the following: (a) simplifying assumptions made in past road design work have made knowledge of the actual pressure distribution unnecessary, and (b) measurements of the contact pressure at all locations (points) in the tire footprint are difficult to make. The actual contact pressure distribution between the tire and the pavement will undoubtedly play a larger role in highway pavement design.

The common assumption is made that the contact pressure is uniform and equal in magnitude to the tire inflation pressure, and that it acts on an area that is circular in shape (1). The theoretical relationships used by highway engineers in design work are simplified considerably by this assumption. However, previous investigations have demonstrated that the actual pressure distribution deviates considerably from the uniform pressure model (2,3).

To determine the shape and size of the contact pressure area, Flugrad and Miller modeled the tire as a modified standing torus in their finite element analysis and predicted an elliptical contact pressure area (4). Another study, by Mack et al., also modeled the tire as a standing torus, and predicted an elliptical contact area as did Flugrad and Miller (5).

O'Neil determined experimentally the net contact pressure area of a statically loaded tire by coating the tire with oil, loading the tire on paper, and allowing graphite particles to stick to the oily

parts of the paper (3). Tracing of the image obtained then gave the desired net contact area.

For statically loaded tires, O'Neil used a nylon pin and proving ring assembly to determine the normal and tangential pressure distributions exerted by the tire (3). A study by Marshak et al. in progress at the University of Texas at Austin uses a digitizing camera and data acquisition system to determine the contact pressure distribution and the net contact area from pressure-sensitive film prints of statically loaded truck tires. The camera digitizes the print and then, using this data base (a) displays the pressure distribution, and (b) calculates the net contact area by summing the picture elements on the television monitor (pixels) on the digitized image, the color intensity of which defines them as a contact area. Clark demonstrated that the pressure distribution for a statically loaded tire is a good approximation for the pressure distribution of a freely rolling tire (6).

Lippmann and Oblizajek used specially designed microtransducers mounted in a ground steel bed to record three components (normal, radial, and tangential) of the pressure distribution under freely rolling tires (7). Shimada et al. conducted a study using piezoelectric sensors mounted in a rotating drum to measure various contact pressure forces at high speeds (2).

The objective of this study is to determine the contact pressures that exist beneath statically loaded truck tires using pressure-sensitive film. The data obtained will indicate what effect the tread pattern, tire inflation pressure, and axle load have on the resulting tire-pavement contact pressure distribution.

EXPERIMENTAL APPARATUS

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The experimental apparatus used in this study consisted of the following components: a load frame for statically loading tires, pressure-sensitive film for capturing the pressure distribution, an optical device (densitometer) for converting color intensity

to pressure, a bidirectional (X-Y) table for precise movement of the print beneath the densitometer, and an HP 3054A data acquisition system.

Tires

The first tire studied was a smooth 10-20 bias ply truck tire used for skid testing. The data from this tire will represent one extreme in the range of tread patterns found in use (as with a tire worn bald) and will thus allow broader conclusions to be drawn about tread patterns and the resulting pressure distributions. The second truck tire studied was a used 10-20 bias ply tire with 3/8 in. of tread depth remaining. This tire is representative of the type of tire and tire condition commonly found on highways today.

Load Frame

The truck tires studied were statically loaded with the load frame shown in Figure 1. This frame was designed so that a hydraulic ram mounted above the tire assembly could deliver a load to the tire through a shaft running through the tire hub. This design allowed the tire to be loaded to better simulate actual use, in contrast to loading the tire, for example, by placing weights on the top of the tire.

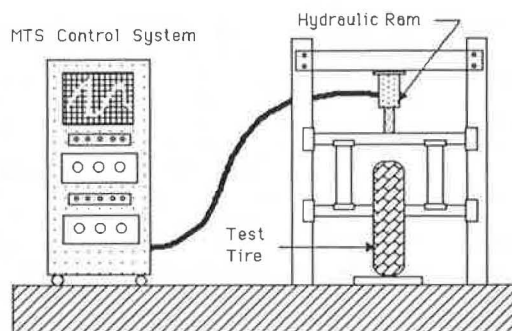


FIGURE 1 Tire load frame.

Pressure-Sensitive Film

A pressure-sensitive film was used, which is capable of capturing the static pressure distribution between contacting bodies. This film consists of an A-sheet and a C-sheet, as shown in Figure 2, the A-sheet containing capsules of developer and the C-sheet providing a developing layer on which the developer acts. The capsules are made in a variety of sizes so that they break when exposed to a certain pressure level. Statistical distribution of the different capsule sizes allows a range of pressures to be captured.

When the two sheets are in their proper orientation and subjected to a pressure, a number of the capsules break and release the developer onto the developing layer; the developer from the A-sheet produces a red spot on the C-sheet, with the intensity of color obtained being proportional to the applied pressure.

Densitometer

The prints developed are read with an optical device called a densitometer (shown in Figure 3). The den-

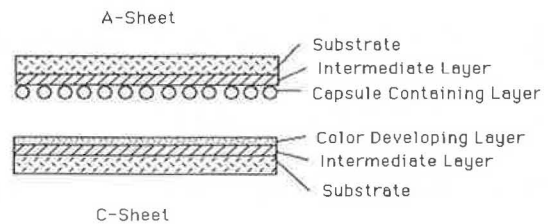


FIGURE 2 Pressure-sensitive film.

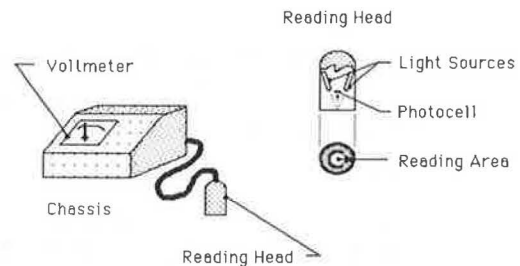


FIGURE 3 Densitometer and schematic diagram of densitometer reading head.

sitometer consists of the reading head and a chassis that contains a voltmeter and calibration controls.

The reading head consists of two symmetrically placed light sources and a photocell. The light sources project beams of light, which pass through a circular opening (0.118 in. in diameter) in the base of the head, striking the print directly below the head, and then reflecting back to the photocell an amount of light proportional to the intensity of color on the print. The photocell outputs a voltage that is proportional to the pressure that was applied to the film; the response of the photocell is that of a first-order system with a time constant of 0.8 sec. The output of the densitometer photocell was connected to a precision voltmeter located in a data acquisition system.

The print developed can be read with the densitometer to determine the pressure at any point or region desired. One important advantage gained by using the densitometer is that a grid reading resolution can be specified, that is, the user can divide the resulting contact area into a grid size with step sizes as small or large as required. This characteristic is important because large pressure gradients occurring in extremely small distances are commonplace, particularly when dealing with bodies such as treaded tires the contact surfaces of which contain numerous discontinuities.

X-Y Table

The small measuring area (0.044 in.²) of the densitometer compared with the large contact area of the truck tire footprint made it necessary to devise a means for automating the print reading process. This was accomplished in part through the use of a bidirectional (X-Y) table that featured high-speed, precision stepper motors driven by an on-board digital control unit. An RS232 interface in the control unit permitted direct control of the X-Y table and data taking by the HP 3054A data acquisition system described in the next section. Errors resulting from miscommunication between the densitometer and the X-Y table controller were avoided because of the exclusive control of the HP3054A over the data-taking process; the print reading time also was kept to a minimum.

Data Acquisition System

An HP 3054A data acquisition system was used extensively throughout all phases of this study. It consisted of the following components: an HP 9816S computer, a dual disc drive, a data acquisition unit, a dot matrix printer, and a multiple pen plotter.

Because of the small measuring area of the densitometer, approximately 6,000 points were measured for each truck tire print in order to map the entire pressure distribution in the contact area. Figure 4 shows the schematic diagram of the print reading system.

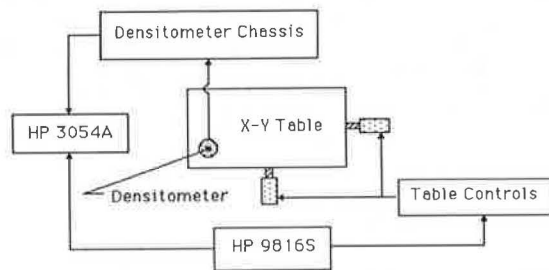


FIGURE 4 Print reading system.

EXPERIMENTAL PROCEDURE

The load application was divided into three parts. The first part was a load ramp in which the load on the tire was increased linearly from zero to full load over a 2-min time period. Part two of the loading consisted of maintaining the full tire load on the paper for 2 min. After this, the tire load was quickly released, the A-sheet was separated from the C-sheet, and the C-sheet was set aside to finish developing. All prints obtained during a testing session were read within 1 hr after the session ended because it was believed that the color intensity on the film might fade with time.

To obtain a pressure print, the A-sheet and C-sheet were taped firmly in their proper orientation to the flat steel plate to prevent erroneous pressure values from being recorded due to the presence of shear forces between the sheets. Also, a piece of shimstock (with a thickness of 0.001 in.) was placed between the tire and the top piece of pressure paper so that expansion of the tire on application of the load was restrained by the shimstock; therefore, only the normal tire load was transmitted to the paper (see Figure 5).

To keep the calibration and experimental procedures as similar as possible, a scheme was devised whereby a known load could be applied to a rubber cube with 1-in. sides (and a Young's modulus roughly equal to the moduli of the truck tires tested) by

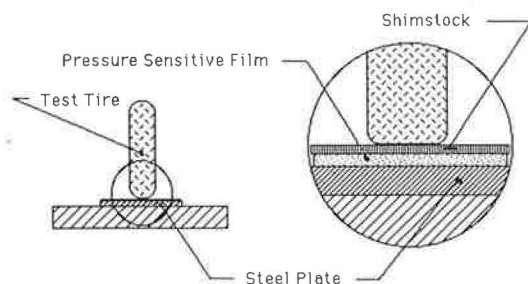


FIGURE 5 Shimstock and pressure-sensitive film configuration.

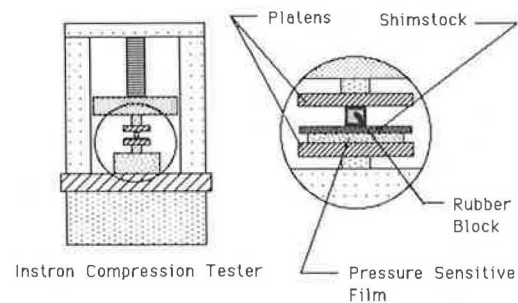


FIGURE 6 Calibration test equipment.

using an Instron compression tester, as shown in Figure 6. Examples of calibration prints obtained with the rubber block and a complete description of the calibration procedure are given by Connell (8).

The data points used to construct the calibration curve were obtained by using the same loading procedure as was used for the tire. The same steel plate and pressure-sensitive film configuration was used, the only difference being that the face of the rubber block touching the shimstock was lubricated to achieve a more uniform pressure distribution. The uniform distribution of known pressure intensity was desired for the calibration prints because the average voltage measured by the densitometer in each of these prints was used as a data point on the calibration curve.

Data points were obtained for each pressure level by averaging voltages in the calibration prints. A second-order polynomial was fitted through the data points to obtain the calibration curve used to convert the voltage arrays to pressures. Because of the sensitivity of the film to its environment, careful attention was paid to ensure that the atmospheric conditions (temperature and relative humidity) were sufficiently close for both calibration and experimental test sessions.

Experiments were conducted with truck tires to demonstrate the effect of tread pattern, tire inflation pressure, and axle load on the resulting contact pressure distribution. Because the pressure-sensitive film is expensive, and because it required about 6 hr to read a developed print, a minimum number of tests were conducted that would still satisfy the goals of this study.

Experiments were conducted by using three different tire inflation pressures (75, 90, and 110 psi) to demonstrate the effect the inflation pressure had on the distribution of pressure in the tire footprint. Two different axle loads were used with this study; the first was a 4,500-lbf load and the second was a 5,400-lbf load (a 20 percent overload).

EXPERIMENTAL RESULTS

The data read by the densitometer from the six pressure prints were stored on disc in the form of arrays of voltages. From the voltage data base, various parameters could be determined, including the net contact area of the tire footprint and the pressure distribution throughout. In addition, the data base could be reduced or converted into equivalent forms (such as equivalent but smaller arrays of pressures and forces); this made it possible to use the data (a) as a means of drawing pressure distributions, (b) to substantiate conclusions about the distribution, and (c) as input to computer programs analyzing pavement performance.

The first form of output used consists of numerical prints that show the pressure that acts on each

grid area in the contact patch; Figure 7 shows a sample numerical pressure print for treaded tire at 90 psi inflation pressure and an axle load of 4,500 lbf. The numerical prints were made by printing the arrays of pressures values in matrix form. General trends in the pressure distribution are difficult to determine from the numerical prints because of the overwhelming amount of data presented for each test conducted. The prints do, however, give a location and the individual pressures that exist in the contact patch.

Operations were performed on the data to reduce the data from an array of 6,000 points (either pressure or force) per print to a number of points appropriate to the application. In general, the operations on the data were performed to accomplish one of two goals: the first goal was to reduce the data to a form suitable for plotting, and the second was to convert the data to an equivalent form compatible with the input requirements of pavement analysis programs.

A three-dimensional plot was chosen over a two-dimensional plot despite the usual assumption that the pressure distribution varies little along the length (in the direction of travel) of the tire. The three-dimensional plots were rotated so that the view chosen best illustrates the pressure profiles along both axes of the footprint (see Figure 8).

The grid dimensions used to make the three-dimensional plots were made nonuniform to preserve regions of high pressure that were isolated because of the presence of the tire shoulder or a tread gap. A moving average scheme was then used to reduce the data

to obtain a single pressure or force acting on each unit area. The plots shown in Figure 8 optimize the viewing variables so that the pressure changes in the contact patch along the two axes and the presence of high pressures at the tire shoulder and along tread gaps can clearly be observed.

A computer graphics program was used to convert each data base of numerical pressure values into discrete points of color on a graphics terminal; controls in the graphics program associated a particular pressure level with a specific color (e.g., yellow points might indicate pressures between 120 and 140 psi). After the entire data base for each print had been read into the graphics program, plots on the color graphics terminal were photographed with a 35-mm camera. Prints made from the slides give a striking summary of the experimental results, showing both the localized pressures and the general trends in pressure found in the contact patch beneath statically loaded truck tires. Prints of the 35-mm slides are given by Connell (8).

DISCUSSION OF RESULTS

The tread type, that is, the particular pattern of treads, plays a dominant role in the determination of the shape of the pressure distribution. The bald tire represents one end of the tread spectrum, the treaded tire the other. The plots shown in Figure 8 illustrate that a bald tire produces a uniform pressure distribution with significant gradients only at the tire center and shoulder.

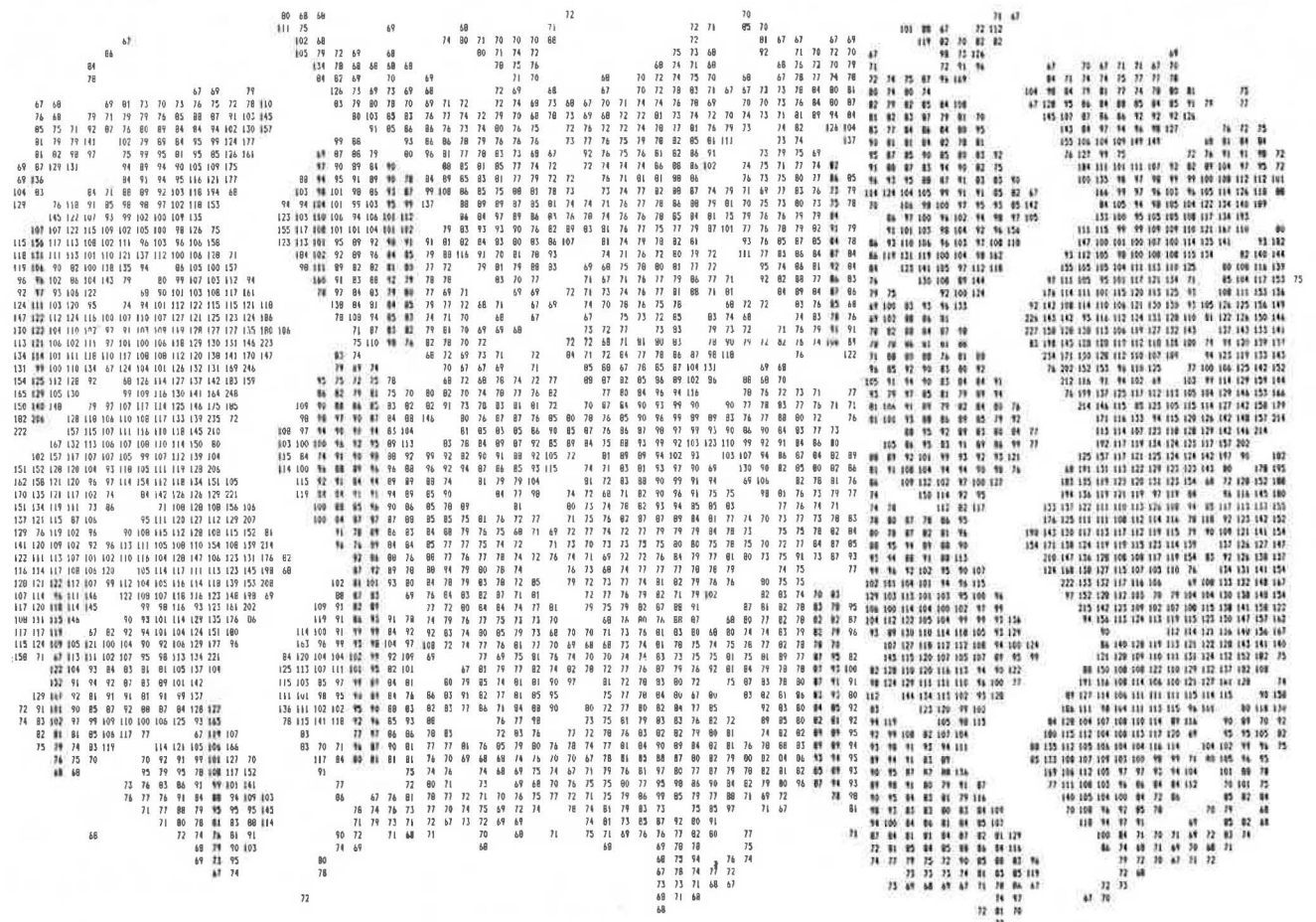


FIGURE 7 Sample numerical pressure print.

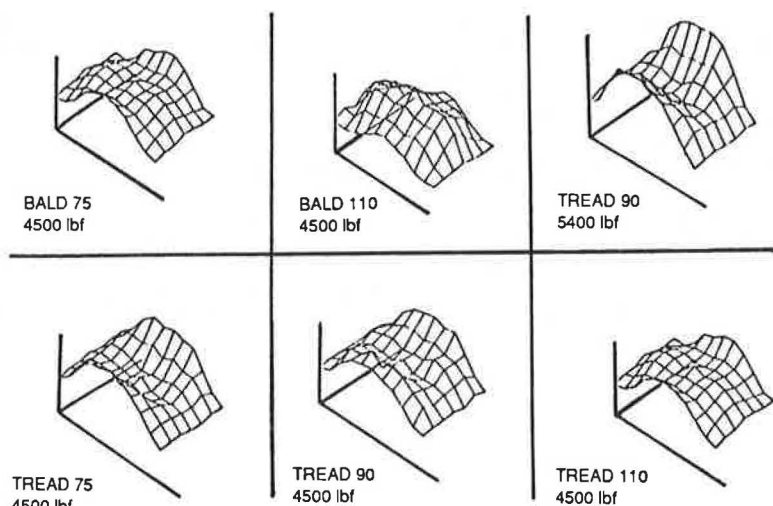


FIGURE 8 Three-dimensional plots of pressure distributions.

With a treaded tire, the pressure distributions have large discontinuities at the tread gaps, within which the pressure is zero. The gaps separate regions of significantly different nonzero pressure levels. This can clearly be observed on the copies of the pressure prints, particularly for the overloaded case (treaded tire at 90 psi and 5,400 lbf), where the circumferential tread gap separates high pressures on the shoulder from medium pressures directly on the other side. This region between the shoulder of the tire and the circumferential gap usually carries the highest pressures.

For a given load, inflation pressure determines the regions of high pressure. Increasing the inflation pressure reduces the crown curvature, thus shifting the high-pressure regions at the tire shoulder to the center of the contact patch.

One other effect of inflation pressure was observed with the treaded tire that supports the use (by highway engineers) of the inflation pressure as the magnitude of the uniform pressure delivered by a tire. The region in the center of the tire, bounded by a circumferential gap on either side, consistently maintained pressures close to the inflation pressure (plus or minus 15 psi) for all of the tests conducted. The high pressures occurred near a tread gap or in the shoulder region where the stress concentration drove the pressures above the range stated.

The axle load is the final parameter the effect of which on the contact pressure distribution was studied. A comparison of the numerical and three-dimensional plots obtained for the treaded tire at rated inflation pressure but for two different axle loads immediately makes clear the following: the pressures in the center region of the tire remain relatively unchanged whereas pressures in the shoulder region increase dramatically.

SUMMARY

The results of this study can be summarized as follows:

1. The tread pattern on a tire was found to have a significant effect on the size of the contact area and the shape of the pressure profiles. Smaller contact areas for treaded tires were observed because the presence of the tread gaps reduced the number of contact points in the tire footprint. The tread gaps

were also demonstrated to separate adjacent regions of vastly different pressure levels. High pressures were consistently found at tread-gap interfaces and at the tire shoulder. As the tread wears, three results can be expected: an increase in the net contact area, a reduction of the peak pressures, and a more continuous distribution.

2. The tire inflation pressure, in general, determined the location of regions of high pressure in the contact patch. Low inflation pressures resulted in large contact regions and high pressures near the tire shoulder region. High inflation pressures produced a significant reduction in contact area and a shifting of high pressures toward the center region of the contact patch.

3. The axle load also affected the contact area and pressure distribution. The 4,500-lbf axle load saturates the center region of the tire footprint with contact pressures approximately equal to the tire inflation pressure. The 5,400-lbf axle load caused deformations in the tire sidewalls and an increase in the load carried by the tire shoulder region.

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Effect of Truck Tire Inflation Pressure and Axle Load on Flexible and Rigid Pavement Performance

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ABSTRACT

Results are presented of an investigation into the effect of truck tire inflation pressure and axle load on flexible and rigid pavement performance as determined by using computer analysis programs. The flexible and rigid pavement analyses were conducted with both an experimental nonuniform contact pressure distribution and a uniform circular contact pressure distribution as input to the computer programs. The results indicated for the flexible pavement analysis that high inflation pressures and heavy axle loads cause higher tensile strains at the bottom of the surface course, but that only heavy axle loads and not increased inflation pressures are responsible for higher compressive strains at the top of the subgrade course. The rigid pavement analysis indicated an insignificant difference between results obtained by using an experimental and a uniform contact pressure distribution model.

A variety of factors are known to contribute to pavement damage, including climate, traffic density, and the loads from automobile and truck tires. Historically, the subject of the effect of truck tire inflation pressure has received little attention for several reasons, including the following: (a) simplifying assumptions made in past road design procedures have made knowledge of the actual pressure distribution unnecessary, and (b) it is difficult to make measurements of the contact pressure over the entire contact area. The influence of tire inflation pressure as well as the contact pressure distribution between the tire and the pavement will both undoubtedly play a larger role in highway design after

their role in causing pavement damage is better understood.

The contact pressure distributions for truck tires loaded at various axle loads and tire inflation pressures were obtained experimentally by using a pressure-sensitive film technique (1). These experimental data were used to determine the effects that the magnitude and shape of the truck tire contact pressure distribution have on the stresses, strains, and deformations developed in the pavement. Computer programs, typical of those used by highway engineers in pavement analysis and design work, are used to determine the strains and stresses of interest for both flexible and rigid pavements. The strains and stresses for an experimental contact pressure distribution will be compared with those obtained by using a uniform pressure model.

The objective of this paper was to determine the effect of tire inflation pressure, tire axle load, and tire pressure distribution model on the strains

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