Measurement of Truck Tire Footprint Pressures

JOHN T. TIELKING AND MOISES A. ABRAHAM

A triaxial load pin array to measure tire footprint pressures was recently purchased by Texas Transportation Institute (TTI). The triaxial load pin has two important advantages over the pressure-sensing film techniques that have been utilized by other researchers: (*a*) tire-pavement shear pressures can be measured, and (*b*) the load pin signal will respond to dynamic tire contact pressure. Preliminary results obtained with the TTI load pin array are described. Footprint pressure distributions were measured for two highway-type radial truck tires and a smooth-tread radial truck tire. The data obtained compared well with footprint pressures measured by pressure-sensitive film at the University of Texas. Comparisons with footprint pressures measured at two major tire companies are also given. Data showing the effects of tire inflation pressure and tire load on footprint pressure developed by conventional and wide-base truck tires are included. The effect of wheel flange offset on conventional truck tire footprint pressure distributions is detected. Recommendations are made for research to systematically investigate other influences, such as tire nonuniformity and the effect of tread wear on truck tire footprint pressures.

Determining tire-pavement contact pressure distributions has become an important research need for further advancement in pavement design (*1*). Today's truck tires, being radial with steel cord reinforcement, are known to operate with footprint pressures that are considerably different from those of the nylon cord bias-ply truck tires for which most of the nation's highways have been designed. Very little information on the tire-pavement pressure distributions produced by modern truck tires is available to the pavement designer.

A variety of methods has been used to measure contact pressure in the tire footprint. A pressure-sensing film and a scanner-digitizer-analysis system were recently used at the University of Texas (*2,3*) in laboratory measurements of truck tire footprint pressures. Piezoelectric sensors now being developed for weigh-in-motion (WIM) appear to provide realistic pavement pressure distributions (*4*) and are an approach that should be pursued for on-the-road measurements. The device that has been found most successful by the tire industry is the triaxial load pin. Several large tire companies and two government agencies (U.S. Air Force and National Aeronautics and Space Administration) have made their own load pins. Most of the work done by industry has been aimed at understanding tire wear and tread design. Goodyear has provided a set of footprint pressure measurements for pavement design purposes (*5*).

The Texas Transportation Institute (TTI) recently purchased a load pin array developed by the Precision Measurement Company of Ann Arbor, Michigan. This company has a long history of custom designing pressure-sensing equipment. Their load pins have the smallest contact area (11.4 mm^2 or 0.018 in^2) of those known to the authors and are currently used by Cooper Tire and the Pirelli-Armstrong Tire Company. The load pin has two important advantages over pressure-sensing film: (*a*) tire-pavement shear pressures can be measured with a triaxial load pin, and (*b*) the load pin signal will respond to dynamic tire contact pressure. This paper describes the initial experience and results obtained with the TTI load pin array. The footprint pressure data measured at Texas A&M (TAMU) are compared with data measured for the same size tires at the University of Texas, Cooper Tire Company, and the Goodyear Tire Company. Recommendations for a research program to further investigate tire-pavement contact pressures are outlined at the end of this paper.

EXPERIMENTAL PROCEDURES

The normal contact pressures at various transverse locations for three different tires were obtained experimentally with tire loads applied by an MTS servo-hydraulic testing machine. A dual flange axle and U-shaped load frame were used to position both wide base and conventional tires in the testing machine. The U-frame was bolted to a load cell that measures the resultant force in the tire footprint. In this arrangement, the axle is fixed (nonrotating) and the load is applied by a contact plate attached to the servo-hydraulic actuator. The actuator moves the contact plate up against the tire until a specified load is reached. Figure 1 shows the laboratory setup.

The contact plate is a box 508 × 508 × 76.2 mm (20 × 20 × 3 in.) made of aluminum plates 12.7 mm (0.5 in.) thick. A movable shoe with 10 load pins slides in the box to obtain data at different transverse locations. Each load pin has three strain gauge channels from which a change in voltage caused by a change in load can be read. Figure 2 shows the contact plate with the shoe inside. A steel scale along the edge of the shoe channel locates the lateral position of the load pin array.

Data Acquisition

Data from the load pin array are acquired by a Daytronic Model 10K6 measurement and control unit. This unit is software controlled by a Compaq Portable 386 computer. A Daytronic program, DAS1, is used to obtain a live display of load pin data from the Daytronic unit. DAS1 displays data in sequential groups of 10 channels per screen page, which permits viewing of the vertical force signal from all 10 load pins simultaneously. The data displayed on the screen are bridge voltage (in millivolts), which changes with load.

As described earlier, the shoe is moved in the contact plate to obtain readings at different transverse locations. Figures 3 through

---

Texas Transportation Institute, Texas A&M University, College Station, Tex. 77843-3135.

5 show the location of the pins with the shoe at three different positions along the median of the footprint of an 11R22.5 tire at a load of 26.9 kN (6,040 lb) and 720 kPa (105 psi) inflation pressure. The precise location of the pins is needed to quantify the distance from the center of the tire at which each contact pressure is obtained. The filled circles in Figures 3 through 5 show the actual contact areas of the load pins, as well as their locations, which are measured to the nearest 1.6 mm (0.0625 in.). The pin centers are spaced 24.5 mm (1 in.) apart.

The procedure adopted to measure the normal pressures is as follows. Initial channel readings are obtained for each load pin (no load applied). The tire load is applied by moving the contact plate up against the tire, and a second set of readings is obtained. Finally, the difference between the two voltage readings and the calibration line for each load pin are utilized to determine the measured pressure. This procedure was repeated for each position of the shoe along the transverse median of the footprint. Table 1 shows the readings obtained for the 11R22.5 tire. Pin 2 was inoperative when these data were taken, so two more shoe positions were used to collect data on Rib 5, using Pins 3 and 4.

The pin contact area is sensitive to tread pattern features. This is the reason a small pin area is desirable. For example, Pin 5 shows zero pressure at Position 3 (Table 1). Referring to Figure 5, one can see that Pin 5 is positioned over a groove (white space in footprint) and thus will not record a pressure.

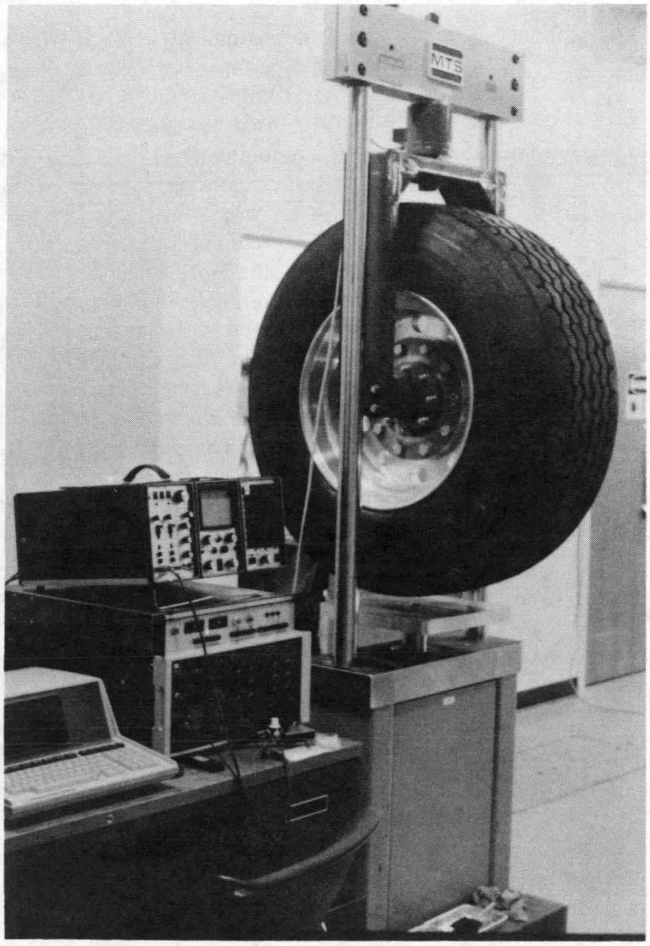

FIGURE 1 **Wide base tire mounted in the testing machine.**

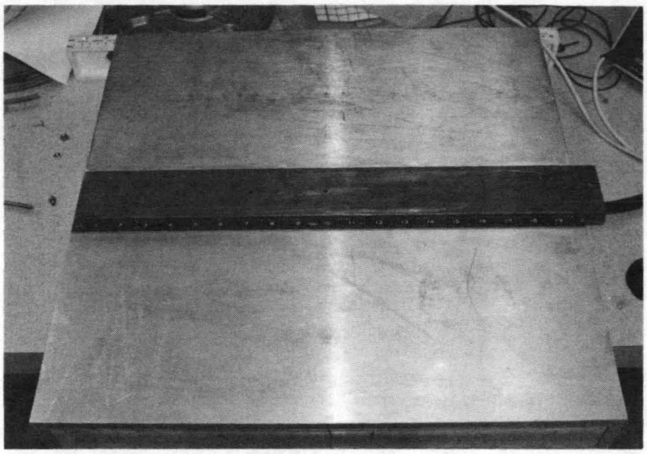

FIGURE 2 **Contact plate and movable shoe with load pin array.**

Table 2 shows the sequential data taken from Table 1 and two other shoe positions. These data show considerable variation in the pressures across the rib. The rib pressures were averaged to make the plots in this paper showing the effects of inflation pressure and tire load on the footprint pressure distribution. Table 3 shows the average rib pressures calculated from data in Table 2.

RESULTS

Footprint pressure measurements were made on three different tires, shown in Table 4. The load limits given in Table 4 are for single tire application with the tire inflated to the design pressure. A slightly lower inflation pressure and load limit are specified when the tire is used as a dual (*6*).

The 11R22.5 size is a conventional radial truck tire, used either as a single, in the steer position, or as duals on drive and trailer axles. The 385/65R22.5 is a wide base tire that is a possible replacement for a dual tire set. These two tires have highway rib-type tread patterns, as pictured in Figure 6. The 11R24.5 tire is a conventional radial truck tire made for research purposes with a patternless tread. The footprint pressures measured with each of these tires are given in the following sections. All pressure distributions in this paper are those found along the transverse median of the tire footprint.

Smooth Tread 11R24.5

This tire has a full tread layer molded without a tread pattern. The smooth tread eliminates the pressure gradients found at rib edges and avoids the difficulty of interpreting data when the load pin spans a kerf (a narrow cut in the tread pattern). This tire has been tested previously by the University of Texas using pressure-sensitive film, and by the Cooper Tire Company using a load pin array similar to that of TTI.

Figure 7 shows the contact pressures measured by the Center for Transportation Research (CTR) at the University of Texas (*2*). Slight tread imperfections are responsible for the scatter of the measured pressures. The 660-kPa (95-psi) peak at the center of

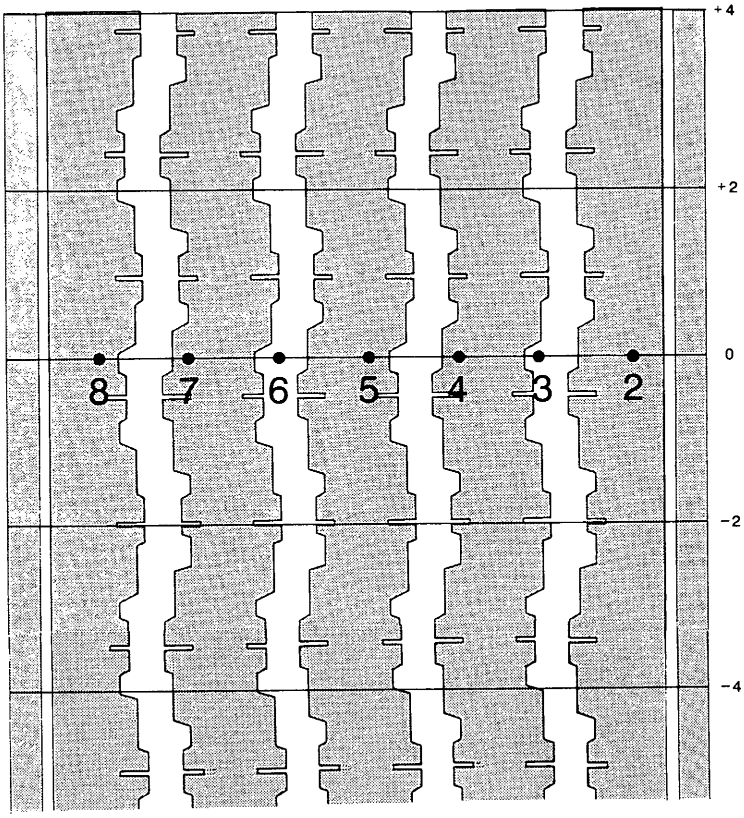

FIGURE 3 Load pin array with shoe at Position 1.

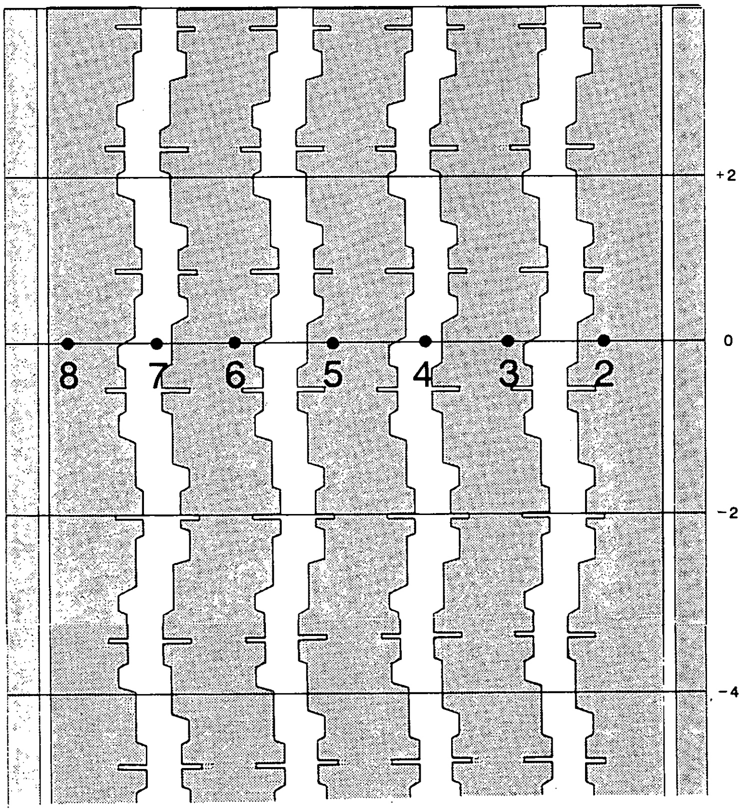

FIGURE 4 Load pin array with shoe at Position 2.

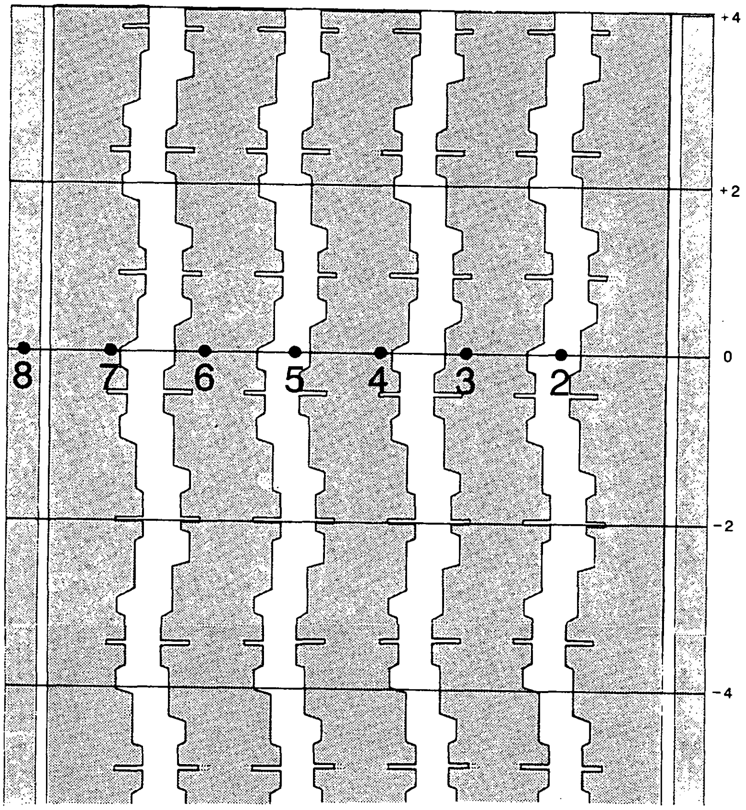

FIGURE 5 Load pin array with shoe at Position 3.

the footprint is caused by the mold parting line, a small ridge of rubber around the tread circumference. The data points measured by the TTI load pin array (TAMU data) are shown with an × in Figure 7.

Figure 8 shows the contact pressure distribution measured by the Cooper Tire Company load pin array, with the tire at a different inflation pressure and a different tire load. The data points measured at TAMU for this pressure and load are shown with an ×.

The agreement between TTI measurements and those of the University of Texas (CTR) and the Cooper Tire Company is very good, considering the sensitivity of interfacial pressure measurements. After test procedures with the smooth tread tire were developed, work with two tires having highway tread patterns was begun.

11R22.5 (Conventional Truck Tire)

Footprint pressures were measured for the 11R22.5 tire at two inflation pressures—720 and 550 kPa (105 and 80 psi)—and at two tire loads—26.9 and 35.6 kN (6040 and 8000 lb)—for each inflation pressure. Figures 9 and 10 show the effect of tire load on footprint pressure for this tire inflated at 720 and 550 kPa, respectively. The data in these and subsequent plots for tires having rib-type tread patterns give the average rib pressures. For example, the distributions across each rib of the 11R22.5 tire at 720 kPa and 26.9 kN load are given in Table 2. These rib distributions were averaged (Table 3) and plotted in Figure 9.

The data in Figures 9 and 10 show the pressure distribution to become somewhat more uniform as tire load increased. As may

TABLE 1 Example Data for 11R22.5 Tire at 720 kPa and 26.9-kN Load

	Position 1			Position 2			Position 3		
pin	Vi	Vf	p	Vi	Vf	p	Vi	Vf	p
3	-7354	-7354	0	-7354	-7874	814	-7354	-7844	744
4	-75	-538	766	-79	-81	0	-82	-906	1476
5	-2	-795	717	-3	-745	655	-5	-5	0
6	-49	-49	0	-45	-1014	1069	-47	-741	814
7	34	-301	372	33	33	0	33	-578	641
8	51	-577	821	62	-420	634	52	-363	586

Vi = initial voltage (mV)
Vf = final voltage (mV)
p = corresponding pressure (kPa)
1 kPa = 0.145 psi

TABLE 2 Measured Pressures

Distance [a] (mm)	Pressure (kPa)	
-98	586	
-83	634	rib 1
-74	820	
-72	641	
-48	372	
-46	814	rib 2
-38	979	
-32	1069	
-6	655	
3	717	rib 3
4.8	1475	
29	766	
30	793	
38	1034	rib 4
45	745	
46	814	
49	724	
72	593	
74	552	rib 5
100	814	

[a] Measured from tread centerline
1 mm = 0.039 in
1 kPa = 0.145 psi

be expected, the average pressure at the higher load is also higher. The average over the entire footprint will be somewhat different. It is well known to tire engineers that the average footprint pressure produced by a tire can be above or below the inflation pressure, depending on tire load. This effect also has been calculated with an analytic tire model (*7*).

It is noted in Figures 9 and 10 that the contact pressure is not exactly symmetrical about the tire plane of symmetry. This is largely because of tire non-uniformity. It is also believed to be because the conventional truck tire was mounted on a wheel with an offset flange. A typical truck wheel is sketched in Figure 11. The wheel mounting flange is offset about 150 mm (6 in.) from the tire plane of symmetry so that the same wheel can be used for dual tires or for single tires. In Figures 9 and 10, the tire load is applied through the wheel flange at 150 mm to the left of the center of the tread (transverse distance). This effectively cantilevers the tire and is believed to contribute to the slight dip in the contact pressure at about 38 mm (1.5 in.) to the right of the tread center. This effect apparently has not been previously noted. It should be investigated further because nearly all conventional truck tires are mounted on a wheel with an offset flange.

TABLE 3 Average Rib Pressure

Distance [a] (mm)	Pressure (kPa)	
-100.0	0	
-85.0	669	(rib 1)
-41.0	807	(rib 2)
-0.5	952	(rib 3)
-40.0	814	(rib 4)
85.0	655	(rib 5)
100.0	0	

[a] Measured from tread centerline
1 mm = 0.039 in
1 kPa = 0.145 psi

TABLE 4 Design Parameters of Tires Tested

Tire Size	Inflation Pressure (kPa)	Load Limit (kN)	Tread Pattern
11R22.5/G	720	26.9	5-rib
11R24.5/G	720	28.6	none
385/65R22.5/J	830	41.7	6-rib

Values given in the 1992 Tire and Rim Association Yearbook (*6*)
1 kPa = 0.145 psi
1 kN = 225 lb

385/65R22.5 (Wide Base Truck Tire)

The wide base truck tire was mounted on a center flange wheel to eliminate the cantilever effect described above. Offset flange wheels are also used to mount wide base single truck tires, but the offset (nominally 96 mm) does not extend outside the contact

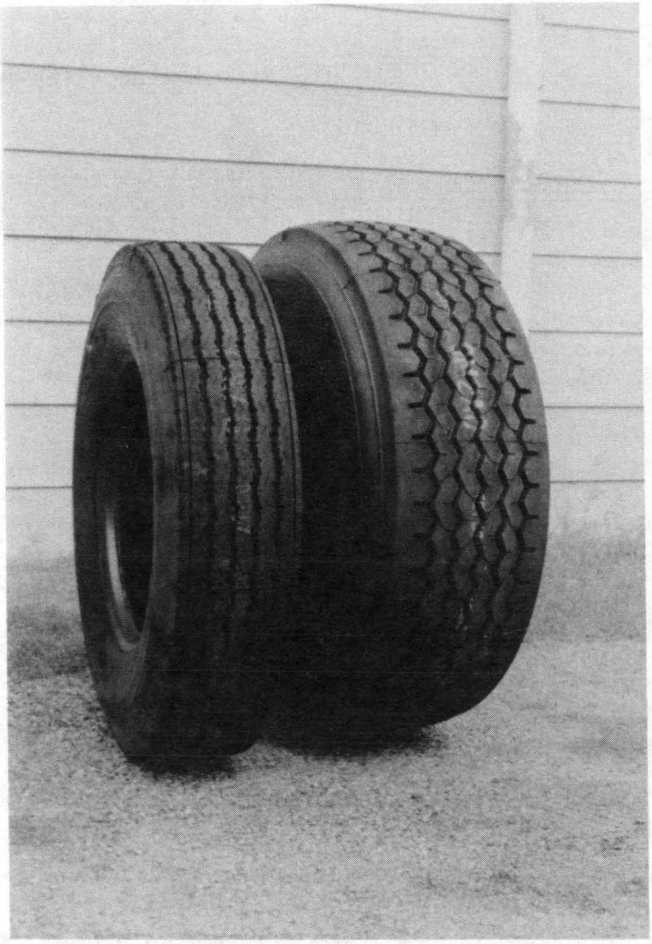

FIGURE 6 Conventional tire (*left*) and wide base truck tire (*right*).

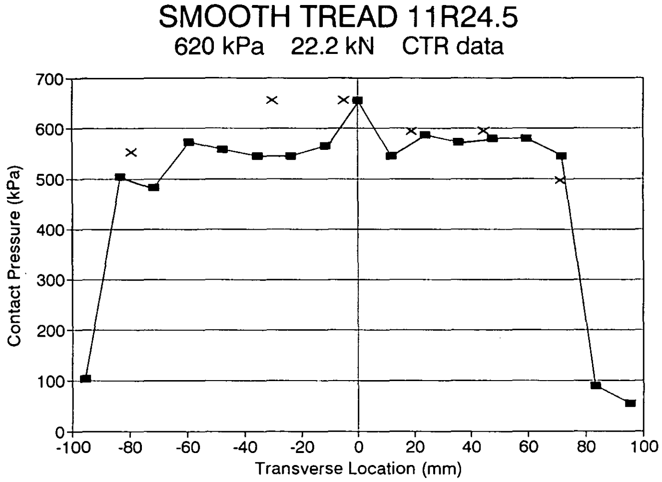

FIGURE 7 Comparison of data measured at TAMU (×) with data measured at the University of Texas (■).

region, so the cantilever effect with wide base tires probably will be imperceptible.

Footprint pressure data on this size tire were previously measured by Goodyear for pavement studies at the Pennsylvania Transportation Institute (*5*). Figure 12 compares the Goodyear data with the data from this study for this tire inflated at 900 kPa (130 psi) and with a 37.8-kN (8500-lb) load. The agreement here is fairly good except on the two central ribs where measurements show about 520 kPa (75 psi) higher contact pressure. It is believed that this can be because of tire variability, perhaps caused by a slight difference in the tire molds. It has not been determined that the tires tested by TAMU and Goodyear came from the same mold or from the same tire-building machine.

Footprint pressures were measured at two other tire inflation pressures, 830 and 660 kPa (120 and 95 psi) and at two tire loads, 26.7 and 40.0 kN (6,000 and 9,000 lb) for each of these pressures. Unlike the conventional truck tire, virtually the same footprint pressures along the transverse median were found for these two tire loads, with the tire at the same inflation pressure. However, inflation pressure has a significant effect when the tire load is held constant. This is seen in Figure 13, where the tire load is held at 26.7 kN.

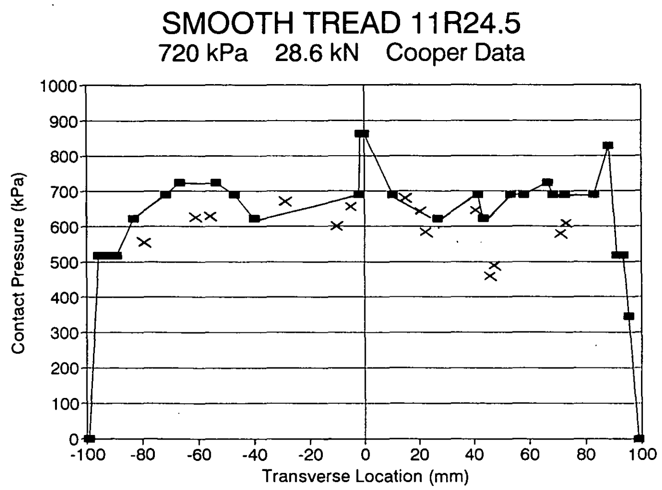

FIGURE 8 Comparison of data measured at TAMU (×) with data measured at the Cooper Tire Co. (■).

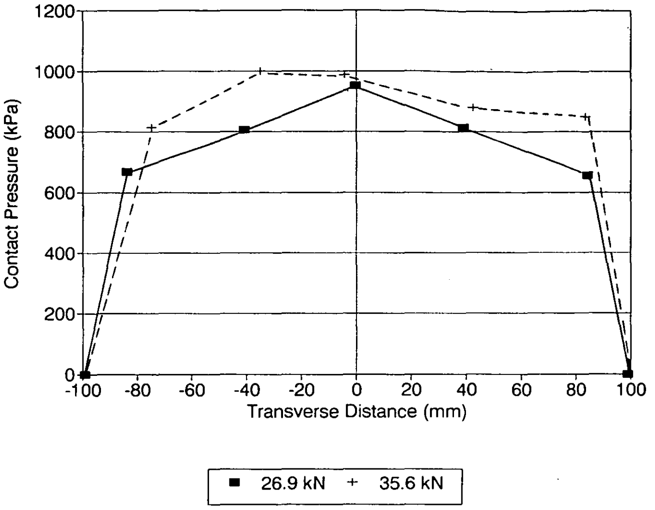

FIGURE 9 Effect of tire load on footprint pressure of 11R22.5 tire at inflation pressure of 720 kPa (105 psi).

Table 5 gives the average contact pressures for the inflation pressures and tire loads at which the wide base tire was tested. These averages are taken along the transverse median of the footprint and are not averages over the entire footprint.

CONCLUSIONS AND RECOMMENDATIONS

The work reported in this paper focused on measurement of tire-pavement pressure distributions, commonly called footprint pressures. Knowledge of footprint pressure distributions is necessary

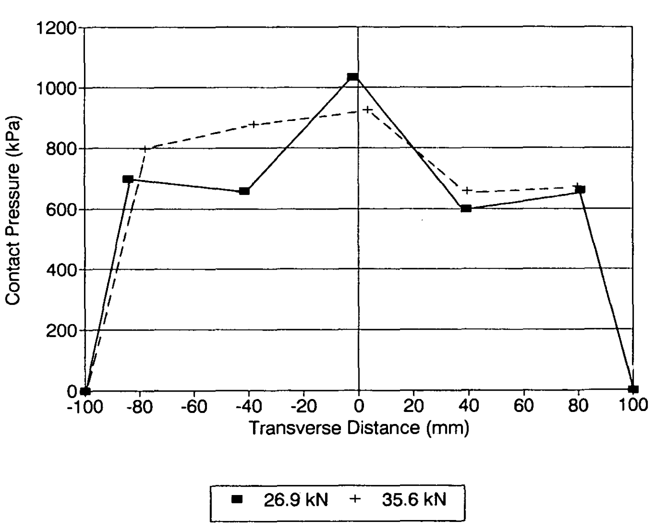

FIGURE 10 Effect of tire load on footprint pressure of 11R22.5 tire at inflation pressure of 550 kPa (80 psi).

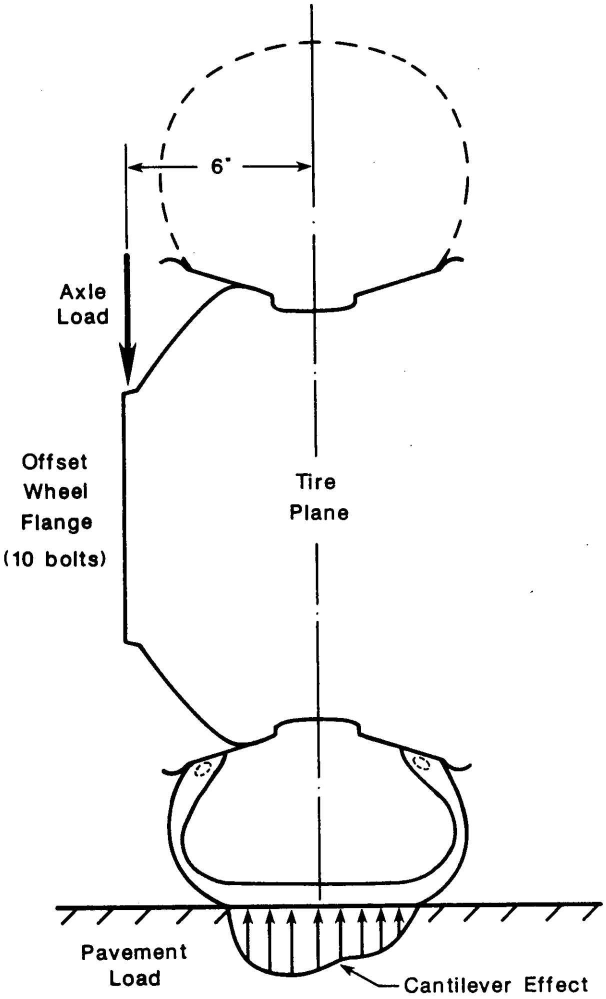

FIGURE 11 Truck wheel with offset flange: effect on pavement load.

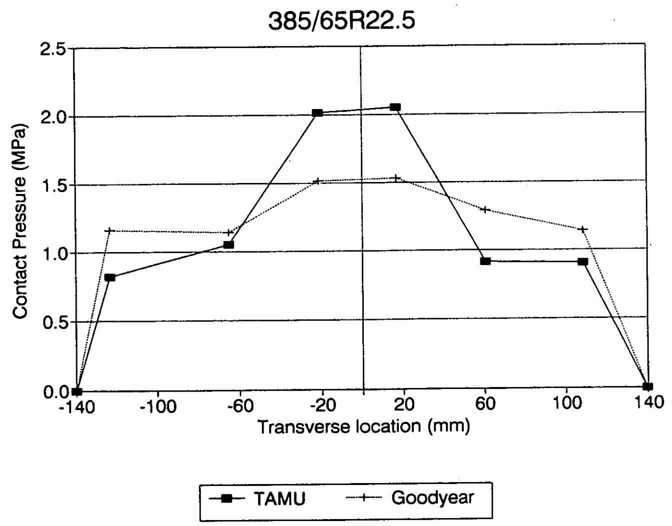

FIGURE 12 Comparison of data measured at TAMU with data measured by Goodyear Tire Company 385/65R22.5 tire at 900 kPa (130 psi) inflation pressure and 37.8 kN (8500 lb) load.

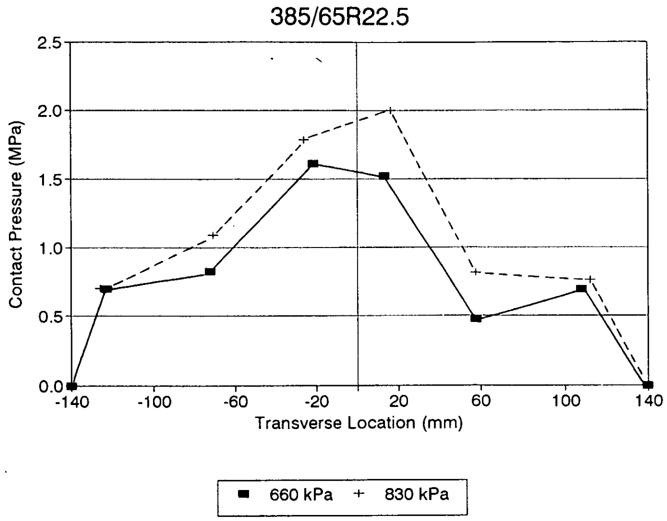

FIGURE 13 Effect of inflation pressure on footprint pressure of 385/65R22.5 tire with 26.7-kN (6,000-lb) load.

to accurately predict pavement damage. The results were found to compare well with data measured for the same size tires at the University of Texas, Cooper Tire Company, and the Goodyear Tire Company. The good agreement is encouraging in view of the extreme sensitivity of interfacial pressure measurements to surface imperfections and contaminants.

Preliminary measurements made to investigate the effects of tire load and inflation pressure have revealed considerable variability in the footprint pressure distributions. Tread wear and tire nonuniformity are two possible sources of footprint pressure variability. The following investigations are recommended to quantify the variability to be expected in tire-pavement contact pressures.

Effect of Tire Footprint Location

Tire uniformity (axisymmetry) has a significant effect on dynamic behavior such as noise and ride. However, no data are available on circumferential uniformity of the footprint pressure. This can easily be investigated by rotating the tire and repeating the footprint pressure measurements. It is recommended that this be done for four equally spaced footprints on each of the three tires tested in the pilot program reported here. It also will be worthwhile to

TABLE 5 Average Contact Pressures for 385/65R22.5 Truck Tire

Tire Inflation (kPa)	Tire Load (kN)	Contact Pressure (kPa)	Data Source
900	37.8	1303	Goodyear
900	37.8	1303	TAMU
830	40.0	1297	TAMU
830	26.7	1193	TAMU
660	40.0	1062	TAMU
660	26.7	972	TAMU

1 kPa = 0.145 psi
1 kN = 225 lb

repeat the measurements on a second tire of the same size and tread pattern to investigate tire-to-tire variability.

Effect of Tread Wear

It is well known that tread wear affects the cornering characteristics of a tire. This may be in part because of changes in footprint pressure caused by wear of the tread profile. A study that includes both worn and new tires of the same size and design is recommended.

Effect of Offset Wheel Flange

The offset wheel flange shown in Figure 11 is used on virtually all heavy trucks operating on U.S. highways. As nonuniformity of tire footprint pressure exacerbates pavement wear, it is worthwhile to test conventional truck tires on both a center flange wheel (specially made) and the usual offset flange wheel to quantify this effect on footprint pressure uniformity. It may be possible to extend pavement life by requiring center flange wheels for conventional tires. Wide base tires will not have this problem.

ACKNOWLEDGMENTS

This work was funded by the Texas Department of Transportation (DOT). The authors thank Bob Briggs of the Texas DOT and Tom Scullion of TTI for their support of this study. John Ragsdale of TTI provided invaluable instrumentation support, including alignment of the load pins.

REFERENCES

1. Smith, H. A. Synopsis of Tire-Pavements Interaction Research. SAE Paper 892455. SAE Truck and Bus Meeting, Charlotte, N.C. Nov. 6–9, 1989.
2. Hansen, R. W., C. Bertrand, K. M. Marshek, and W. R. Hudson, *Truck Tire Pavement Contact Pressure Distribution Characteristics for Super Single 18-22.5 and Smooth 11R24.5 Tires*, Report 1190-1. Center for Transportation Research, University of Texas at Austin, July 1989.
3. Pezo, R. F., K. M. Marshek, and W. R. Hudson, *Truck Tire Pavement Contact Pressure Distribution Characteristics for the Bias Goodyear 18-22.5, the Radial Michellin 275/80R24.5, the Radial Michellin 255/70R22.5, and the Radial Goodyear 11R24.5 Tires.* Report 1190-2F. Center for Transportation Research, University of Texas at Austin, Sept. 1989.
4. Kasahara, A., K. Himeno, K. Kawamura, and S. Nakagawa. Performance of Asphalt Pavements at Bibi New Test Road in Japan Related to Their Bearing Capacity. *Proc. 7th International Conference on Asphalt Pavements*, Vol. 1: Design 1992, pp. 106–123.
5. Sebaaly, P., and N. Tabatabaee. Effect of Tire Pressure and Type on Response of Flexible Pavement. In *Transportation Research Record 1227*, TRB, National Research Council, Washington, D.C., 1989, pp. 115–127.
6. *1992 Yearbook.* The Tire and Rim Association, Inc., Copley, Ohio, 1992.
7. Tielking, J. T. A Finite Element Tire Model. *Tire Science and Technology*, Vol. 11, Nos. 1–4, Jan.–Dec. 1983, pp. 50–63.
8. Tielking, J. T., and F. L. Roberts. Tire Contact Pressure and Its Effect on Pavement Strain. *Journal of Transportation Engineering*, Vol. 113, No. 1, Jan. 1987, pp. 56–71.

Publication of this paper sponsored by Committee on Surface Properties–Vehicle Interaction.