Automated Acquisition of Truck Tire Pressure Data

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Recent field studies have established that operational truck tire inflation pressures are much higher than those typically assumed in the pavement design process. Field data have shown that tire inflation pressures for trucks operating on the highway average between 95 and 100 lb/in.^{2} (psi), whereas 75 to 80 psi is usually assumed in pavement design. Other work has shown that these tire pressures are not uniformly distributed across the area of contact between the tire and the road surface. One of these studies indicated that contact pressures at the outer edge of the contact area can be as high as twice the tire inflation pressure. This situation is suspected of causing significant levels of premature failure in pavement structures in Texas. Presented in this paper are the results of a study into the feasibility of automatically monitoring the contact tire pressures produced by trucks while they are in motion by monitoring tire footprint dimensions and weight. The work undertaken has included *(a)* A review of principles of tire contact pressure measurement and available sensor technology; *(b)* An assessment of the feasibility for using each principle/technology for truck contact pressure measurement; and *(c)* development of the concept for an independent tire contact pressure measurement system, as well as options for incorporating an automatic contact tire pressure-sensing feature into current operational truck weigh-in-motion systems. Described in this paper are the results of work performed by the Texas Transportation Institute, sponsored by the Texas State Department of Highways and Public Transportation (hereinafter referred to as the Department) in cooperation with the Federal Highway Administration of the U.S. Department of Transportation.

Recent field studies indicate that operational truck tire inflation pressures are higher than normally assumed. Therefore a concept has been developed for measuring tire contact pressures as part of a weigh-in-motion system.

TIRE CONTACT PRESSURE MEASUREMENT

Tire contact pressure is the pressure on the surface of the pavement at the tire/surface interface. This value depends on both the applied load and the area to which it is applied. The acquisition of tire contact pressure data requires either direct or indirect measurement of the load on each tire and the lateral and longitudinal dimensions of the contact area.

There are basically two approaches available for automatically acquiring truck tire contact pressures. One of these is to provide the load input from conventional truck weigh-in-motion (WIM) equipment and to obtain truck tire footprint information from one or more other sensors. Another approach is to design a sensor that directly measures the tire contact pressure.

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TIRE CONTACT AREA MEASUREMENT

No method currently exists for directly measuring the tire contact area of a moving vehicle. Therefore, the computation of the tire contact area is necessarily approximate, because the shape of the tire footprint is neither regular nor constant. As shown in Figure 1, it is nearly circular at the leading and trailing edges and reasonably straight on the sides. As tire inflation pressure increases, the tire footprint becomes smaller, less rectangular, and more circular. Three methods are presented in this section for estimating tire contact area by measuring selected characteristics of the tire footprint. These are: axle sensor arrays; axle sensors in combination with WIM sensors; and pressure-sensitive devices. (This latter technology has been applied to discriminating between single and dual tires on the same end of an axle by at least one vendor of WIM systems, but their product has been discontinued and was not appropriate to the measurement of the tire contact area.)

Use of Axle Sensors for Tire Contact Area Measurement

One way to measure the tire contact area is to detect the edges of the tire footprint to provide values for the geometric parameters of the shape of the footprint. For example, if the footprint were rectangular, it would be necessary only to detect the leading, trailing, and side edges of the footprint according to the following idealized procedure.

Three axle sensors are used in the configuration shown in Figure 2. Two are placed laterally in the traffic lane, perpendicular to the direction of travel. The third is placed diagonally, at an angle of 45° to the direction of travel. Vehicle speed measurement is provided by the two lateral axle detectors. The length of the tire footprint is measured by the first lateral axle sensor. The diagonal axle sensor aids in computing the width of the tire footprint.

Figure 3 shows an example of the tire contact area measurement process. Vehicle speed is obtained from the actuation times of the two lateral axle detectors as follows. At time T_1, the leading edge of the tire strikes the first lateral axle sensor, producing the leading edge of an electrical pulse from electronic detection circuitry connected to the sensor. The electrical pulse stays up until time T_2, when the trailing edge of the tire leaves the first lateral axle sensor. At time T_3, the outer leading edge of the tire makes contact with the diagonal axle sensor, resulting in an actuation and producing the leading edge of a second electrical pulse. This electrical pulse stays up until time T_4, when the inner trailing edge of the tire leaves the diagonal

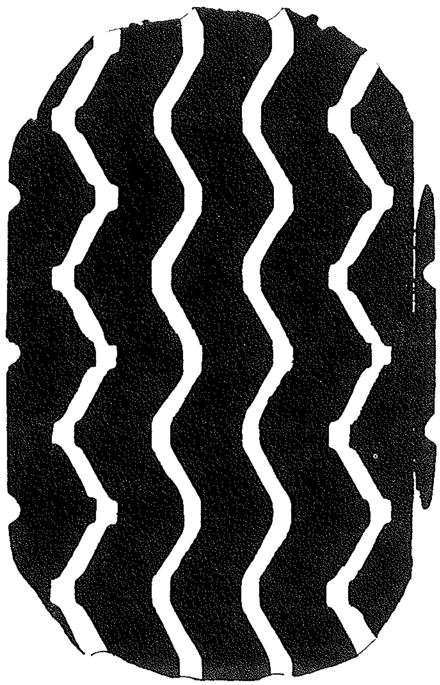

FIGURE 1 Typical tire footprint.

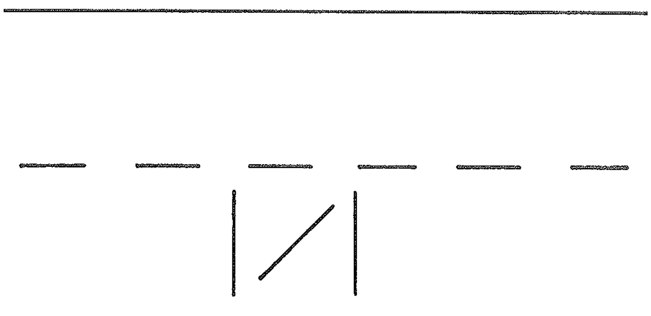

FIGURE 2 Axle sensor configuration.

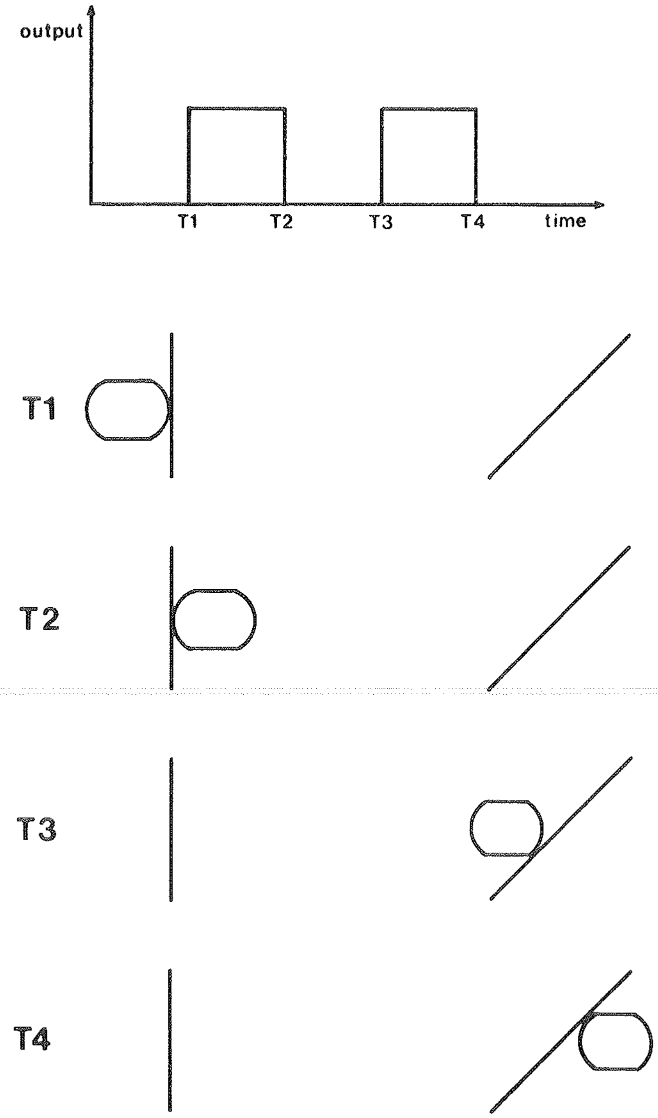

FIGURE 3 Axle sensor operation.

axle sensor and the electrical pulse drops to zero. At time T_5, the leading edge of the tire strikes the second lateral axle sensor, producing the leading edge of another electrical pulse. The electrical pulse stays up until time T_6, when the trailing edge of the tire leaves the second lateral axle sensor. The times at which the leading edge of the tire strikes the two lateral axle sensors are used to compute vehicle speed according to the following equation:

$$\text{Speed} = D/(T_5 - T_1) \tag{1}$$

where speed is in inches per second, actuation times T_i are in seconds, and D is the distance in inches between the perpendicular axle detectors. The footprint length is then calculated from the following equation:

$$\text{Length} = (T_2 - T_1) \times \text{speed} \tag{2}$$

where length is in inches.

Assuming the diagonal axle sensor is at an angle of 45°, the width of the hypothetical rectangular tire footprint is then calculated with the following equation:

$$\text{Width} = [(T_4 - T_3) - (T_2 - T_1)] \times \text{speed}/1.414 \tag{3}$$

where width is in inches. The constant 1.414 is a correction factor for the 45° angle.

Combining Equations 1 through 3 provides an equation for computation of the tire contact area from the actuation times of the sensor configuration shown in Figure 2.

$$\begin{aligned}\text{Area} &= (T_2 - T_1) \times [(T_4 - T_3) - (T_2 - T_1)] \times \text{speed}^2 \\ &= (T_2 - T_1) \times [(T_4 - T_3) - (T_2 - T_1)] \\ &\quad \times [D/(T_5 - T_1)]^2\end{aligned} \tag{4}$$

where the area is the tire footprint contact area in square inches. If the weight of a wheel is known, then the average tire contact pressure over the tire footprint is given by

$$\text{Pressure} = \text{weight/area}$$

where the tire contact pressure is psi, the weight of the tire is in pounds, and the area is in square inches.

Equipment for obtaining the wheel weight is discussed in the next section. With regard to measuring the tire contact area using the procedure described above, it is useful to consider the assumptions on which the derivation is based and the impacts of deviations from the assumed conditions on the measurements. The assumptions made were that

1. The tire is rectangular,
2. The tire contact area is constant,
3. The speed through the sensor area is constant,
4. The distances between sensors are constant, and
5. The actuation times are precisely recorded.

Each of these assumptions will be examined in the following paragraphs.

The accuracy of automatic measurement of tire contact area using axle detectors is dependent on the assumed shape of the tire footprint. It is not necessary that the assumption of a rectangular area be met, but it is necessary that algorithms be developed that can relate the actual tire contact area to the actuation times recorded.

Tire footprints are generally rectangular with circular leading and trailing edges and straight side edges when inflated at approximately 80 psi. However, as inflation pressure is increased, the footprint becomes smaller and more circular for the same load. As this occurs, the axle sensor configuration of Figure 2 will not work as intended. The peak on the leading and trailing edges of the tire will cause the measurement system to overestimate the effective length of the tire footprint. Conversely, the shape of the same leading and trailing edges may result in an underestimate of the tire width because the front edge of the tire rather than the outer edge may be activating the diagonal sensor. This is particularly true for diagonal sensors, which make an angle of less than 45° with the lateral dimension of the roadway. However, it appears that the length and width measurement errors are offsetting. The degree to which this circumstance holds in actual field conditions needs to be evaluated.

The impact of tire shape on tire contact area measurement with axle sensors can be considered by analyzing Figure 4, which is based on Figure 1 and an actual tire footprint. The actual area of the footprint is 66.97 in.^{2}. The maximum length of the pattern is 10.84 in. and the maximum width is 6.95 in. The inflation pressure is 80 psi. Assuming that the truck with this tire is travelling at 55 mph and it strikes the first lateral axle sensor at time $T_1 = 0$, the following times will be recorded:

$T_1 = 0.000$ sec
$T_2 = 0.011$ sec
$T_3 = 0.012$ sec
$T_4 = 0.032$ sec
$T_5 = 0.198$ sec
$T_6 = 0.209$ sec

Then, from Equations 1 through 3:

Speed = 192 in./0.198 sec = 969.697 in./sec (= 55.00 mph)
Length = 0.011 sec × 969.697 in./sec = 10.67 in.
Width = [(0.032 − 0.012 sec) − 0.011 sec] × 969.697 in./sec /1.414 = 6.17 in.

The measured contact area is then

Area = 10.67 in. × 6.17 in. = 65.83 in.^{2}

This value compares favorably with the 66.97 in.^{2} in the actual area of the tire footprint. However, it remains to be seen whether such results can be obtained from a full range of tire types, sizes, tread conditions, and inflation pressures.

Laboratory studies of the variations of tire footprint shape and area under load have produced results that indicate that as the load increases, so does the area of the tire contact footprint. The rate of increase is dependent on tire construction and the tire inflation pressure. Figure 5 reproduces plots of gross tire contact area versus load for different inflation pressures for one common type of truck tire. Figure 6 shows plots of gross tire contact area for radial (I and II) and bias (VII and VIII) tires as a function of load. Both Figure 5 and Figure 6 indicate that gross contact area is a linear function of load for the reasonable range of loading.

Laboratory and field studies are needed to determine the exact relationships among tire contact area, effective tire width, effective tire length, tire inflation pressure, and tire loading for moving trucks. As indicated in the previous paragraph, a considerable body of laboratory data now exists, so that extensive laboratory work will not be necessary for the development of operational automated tire contact area measurement techniques and devices. However, test track and field test runs will probably be needed to provide the required information.

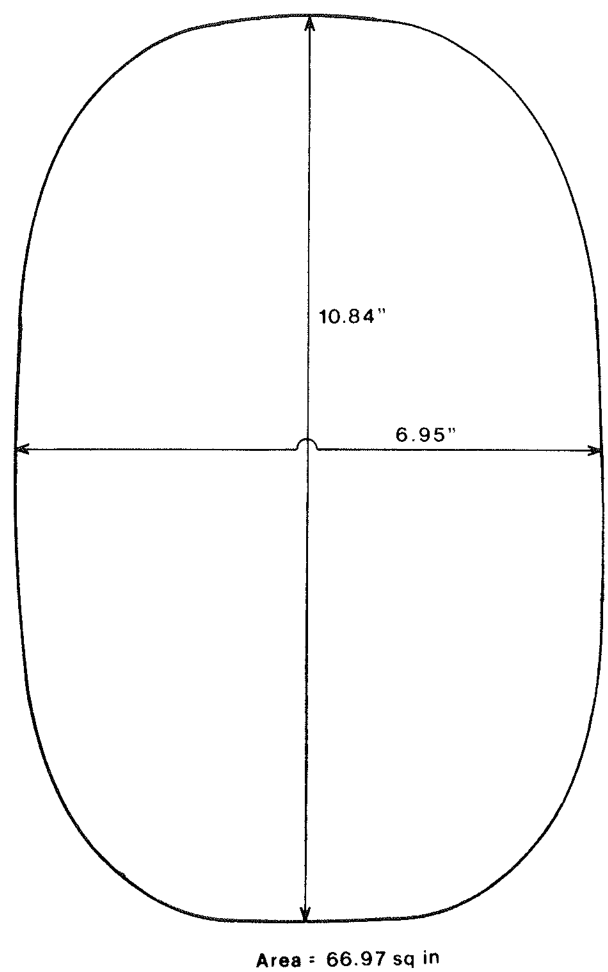

FIGURE 4 Tire footprint dimensions.

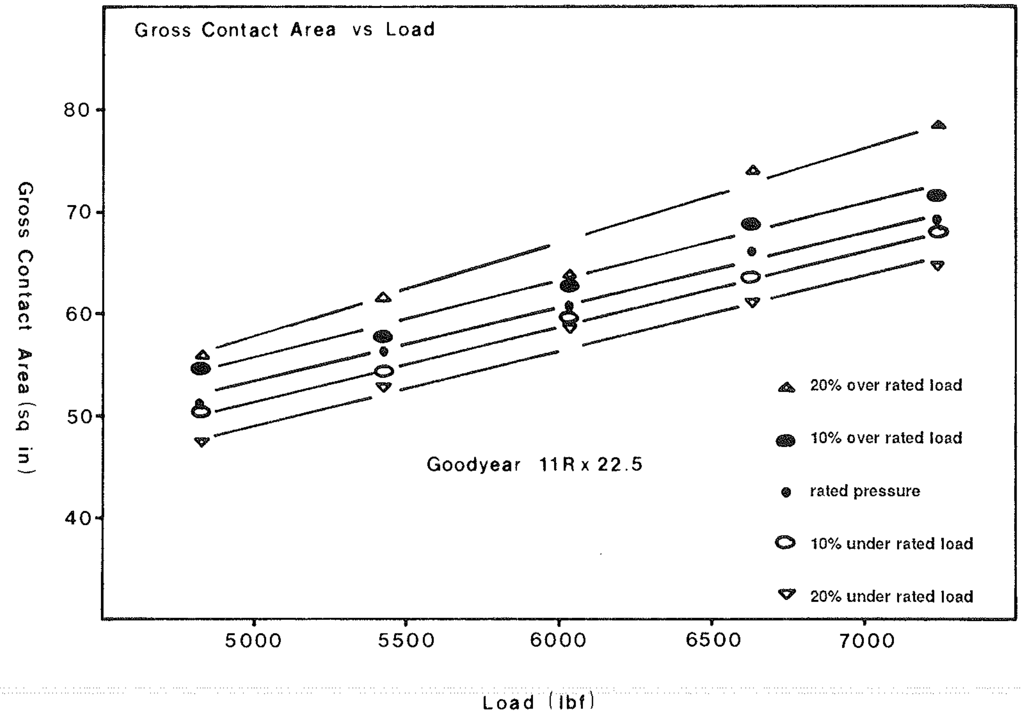

FIGURE 5 Gross tire contact area versus load and inflation tire pressure *(1)*.

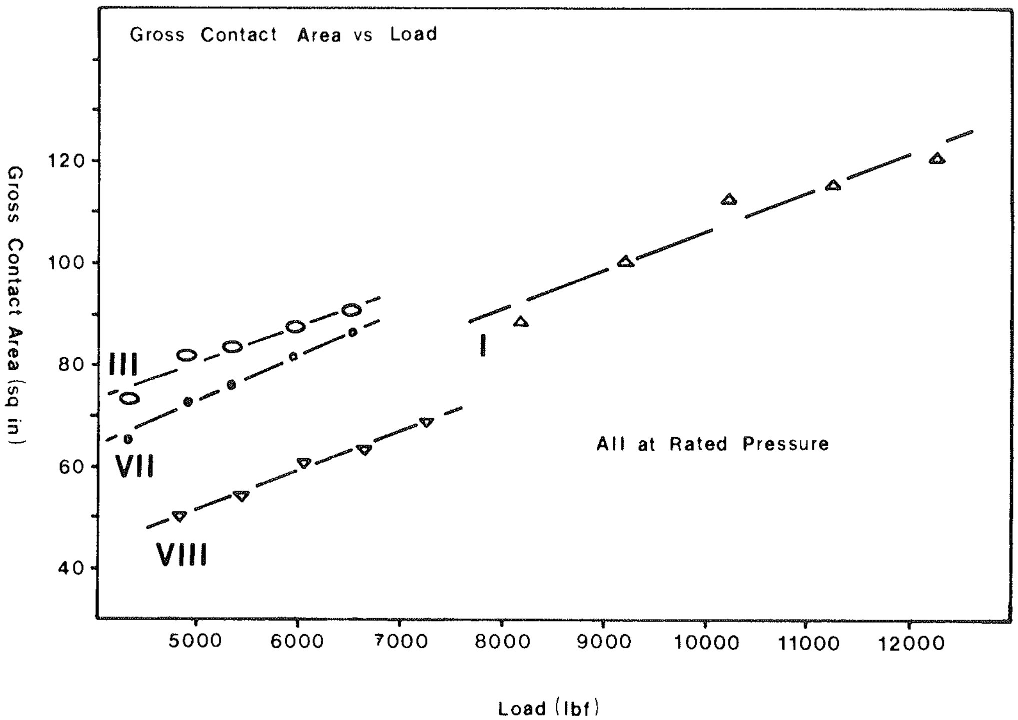

FIGURE 6 Gross tire contact area versus load for different tires *(1)*.

The assumption of constant vehicle speed is reasonable if the total length of the sensor array is less than approximately 30 ft and there are no conditions that are likely to cause vehicles to brake or accelerate. For this reason, monitoring sites should be chosen so that conflicts with other traffic are minimized and the variable speeds found in traffic congestion are avoided.

The distances between sensors are required for computation of speeds and subsequently tire contact area. An error of 6 in. in an assumed distance of 16 ft (a commonly used distance for speed measurement) for a vehicle traveling 55 mph can result in a 1.59 percent speed error and a 3 percent error in calculating the tire contact area for rectangular tire footprints. This error rate alone is not significant, but because it can be added to other sources of error it is clear that care must be taken in sensor placement.

Nearly all automatic electronic traffic data-collection systems acquire data digitally. That is, the electronic system controller checks the status of each axle detector at preset intervals to determine if it has been actuated. This interval is usually approximately 1 ms. This use of periodic sampling limits the accuracy of speed and therefore tire-dimension measurements. For example, assuming a sensor spacing of 16 ft, an actual vehicle speed of 55 mph, and a sampling interval of 1 ms, an error of ½ ms in the actuation time for each axle sensor is expected. This would result in a 1 percent error in the measurement of tire contact area due solely to this source. Again, this error is not serious alone but it can contribute to unacceptable performance. The measurement of tire contact area requires as much precision as possible within the constraints of budget and technology.

Use of a Combination of Axle and WIM Sensors for Tire Contact Area Measurement

The simplest method for the addition of a tire contact area measurement feature to an existing WIM system is shown conceptually in Figure 7. The Radian WIM system sensor configuration used by the Department was chosen for illustration. The diagonal line shown in Figure 7 is an axle sensor. Vehicle speed measurement is provided by the Radian system using inductive loops. The weight transducer acts as both a weight and an axle sensor for the measurement of the length of the tire footprint. The diagonal axle sensor aids in computing the width of the tire.

Figure 8 shows an example of the tire contact area measurement process. Vehicle speed is obtained from the WIM system using inductive loops. At time T_1 the leading edge of the tire strikes the WIM sensor, producing the leading edge of an electrical pulse of the weight signal. The electrical pulse stays up until time T_2, when the leading edge of the tire begins to leave the WIM sensor. At time T_3 the tire has left the WIM sensor entirely and the electrical pulse drops to zero. At time T_4 the tire footprint makes contact with the diagonal axle sensor, resulting in an actuation and producing the leading edge of a second electrical pulse. This electrical pulse stays up until time T_5, when the inner trailing edge of the tire footprint leaves the diagonal axle sensor and the electrical pulse drops to zero.

Given the vehicle speed and the axle sensor actuation times, software can be developed to compute the approximate tire contact area using the following equation:

$$\text{Area} = (T_3 - T_2) \times [(T_5 - T_4) - (T_3 - T_2)] \times \text{speed}^2$$

where the T_i are in seconds and the speed is in inches per second.

Use of Pressure-Sensitive Mats for Tire Contact Area Measurement

Several types of pressure-sensitive material exist that could be used for the automatic measurement of tire contact area. These sensors operate on the principle that the area of the mat over which the tire passes can be automatically identified. This objective can be accomplished in several ways. Two of these are: *(a)* the fabrication of a pattern of pressure-sensitive elements as indicated in Figure 9; and *(b)* the recording of the pattern of activation of a solid pressure-sensitive sheet. Although these approaches have not yet been applied to the measurement of tire contact area (or pressure), they have been used for several years in commercial and industrial applications. The most commonly used material for this purpose is

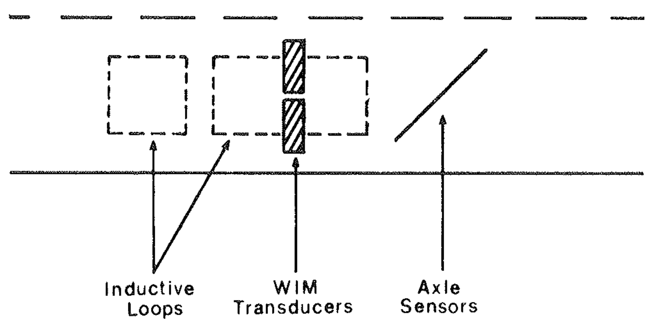

FIGURE 7 Axle sensor configuration for modified Radian WIM installation.

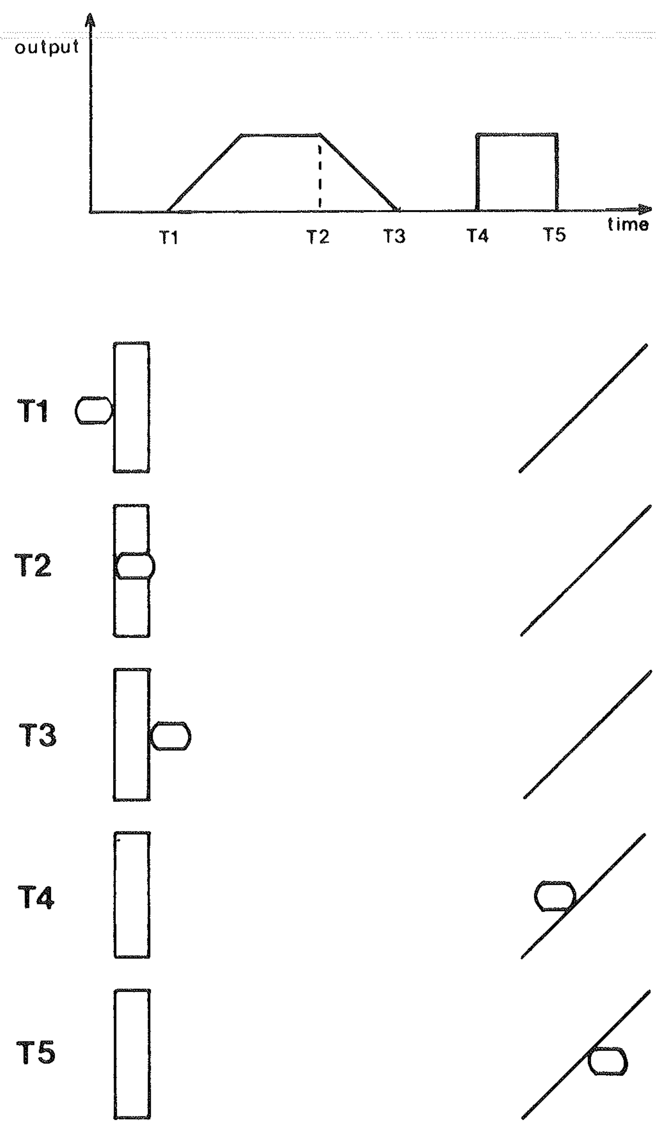

FIGURE 8 WIM/axle sensor operation.

piezoelectric film. It is discussed briefly in the section dealing with specific sensor technologies.

The pattern of pressure-sensitive elements shown in Figure 9 is used to detect the tire contact area by determining if there is a load on each element during a single sampling cycle of the digital electronic traffic-monitoring system. Each element covers a known surface area, so that the total contact area can be calculated by adding the areas of the actuated sensing elements. For example, consider Figure 10, which shows the tire footprint of Figure 1 superimposed on the pattern of pressure-sensitive elements from Figure 9. The tire actuates 5 percent of the elements on the mat, so it is assumed to have an area that is 5 percent of the 1,296 in.^{2} mat area, or 64.8 in.^{2}. This compares to the 66.97 in.^{2} area that was actually measured.

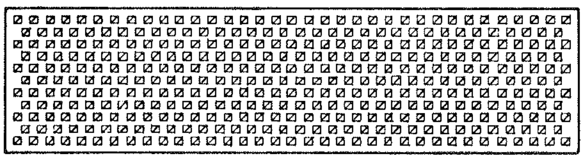

FIGURE 9 Pattern of pressure-sensitive elements.

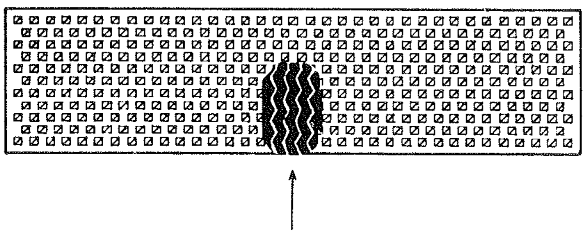

FIGURE 10 Operation of pattern of pressure-sensitive elements.

Clearly the density of the elements has a direct effect on the accuracy of the measurements. The more elements that are placed in a given area, the more accurate will be the estimate of the tire contact area. In order to provide an accuracy of ± 5 percent, it will be necessary to provide one sensor element for each in.^{2} of the mat surface area.

This type of sensor also obviously has a possible application to direct measurement of tire contact pressure. This approach is discussed in a later section.

Another possible approach is to construct a composite mat consisting of two sheets, each of which contains strips of pressure-sensitive material. As shown in Figure 11, the first sheet would have the strips oriented to correspond with the longitudinal direction of the traffic lane; the second sheet would have the strips oriented laterally so that they are perpendicular to the strips on the other sheet. As illustrated in Figure 12, when the tire footprint is covering any portion of a strip it is detected. The coordinates of the intersections of actuated longitudinal and lateral strips can then be determined. If there are a total of 324 intersections of longitudinal and horizontal strips covering 1,296 in.^{2} and 17 of these are actuated, then the calculated tire contact area is 68 in.^{2}. As with the use of the pattern of individual pressure elements, the density of the strips has a direct effect upon the accuracy of tire contact pressure.

The third application of pressure-sensitive material to the measurement of tire contact area is to use a single solid sheet,

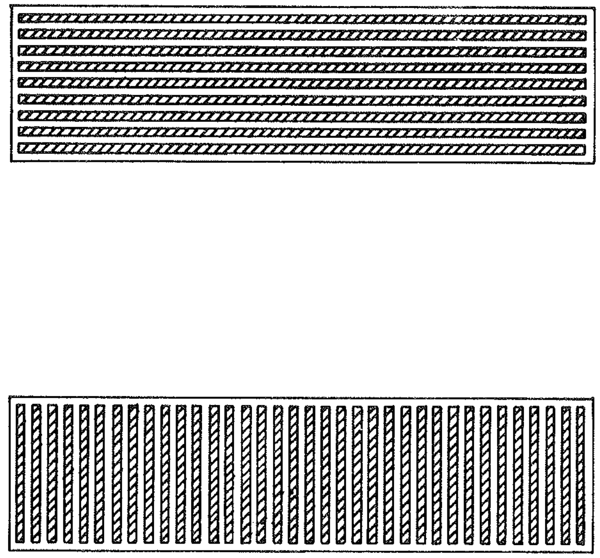

FIGURE 11 Pattern of pressure-sensitive strips.

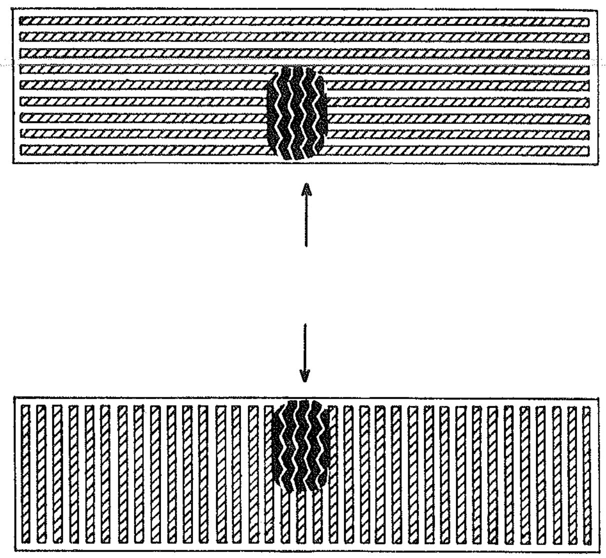

FIGURE 12 Operation of pattern of pressure-sensitive strips.

taking advantage of the time it takes for the actuation response of an area of the material to reach the electronic detection circuitry. When the tire is on a specific area, an excess electrical charge is generated in the crystalline structure of the pressure-sensitive material. This excess charge travels through the material at a known speed. There are receptors along the edges of the mat that receive these generated signals and interpret the times they are received as actuations of the surface contact area. Although a moving tire is a more complex phenomenon than others that this approach has been used to address in commercial, industrial, and military applications so far, algorithms could be developed for its successful application to tire contact area measurement.

The three configurations of pressure-sensitive material already described have been discussed in the context of a mat. However, it is also possible that a narrow strip could detect tire length in a manner similar to an axle detector while it sensed tire width as a pressure sensor.

DUAL TIRES

The preceding discussion has applied to measuring the tire contact area of a single tire. However, it is most common that heavy trucks have dual tires on each side of an axle (except for the steering axle). The use of the diagonal axle sensor will require that statistical relationships be developed between the apparent width produced by two tires together, which appear to be one to the sensor and the actual contact area of the pair of tires. Alternatively, if a piezoelectric cable is used as the diagonal axle sensor, the width of each tire can be determined from the difference in the magnitude of the cable output produced by the number of tires. The discussion of piezoelectric cable in the following section on axle sensors includes a figure that clarifies the operation of this sensor for discriminating between one and two axles.

Any of the three pressure-sensitive material sensor configurations are capable of determining if an actuation is caused by one or two axles. This is due to the fact that each has the ability to monitor what is happening in each section of the mat at any time.

APPLICABLE SENSOR TECHNOLOGIES

This section presents a discussion of vehicle sensor technologies that are applicable to the objective of automatically measuring tire contact pressures. Also included is a description of other technologies not now in use for vehicle sensing that could be applied to this problem.

Axle Sensors

Pneumatic Tubes

Pneumatic tubes are easily the most widely used axle sensor. They operate by the rapid compression of a trapped volume of air in a section of tubing with the subsequent mechanical actuation of a diaphragm. The actuation of the diaphragm in turn produces an electrical pulse that is delivered to the recording circuitry. Pneumatic tubes are always installed in portable situations. These devices have several advantages for application to tire contact area measurement. They are inexpensive and can be easily installed by one person in less than 10 min under low traffic conditions. These sensors are both durable and reusable. The operational life is approximately 6 months under daily use and moderate traffic levels.

Pneumatic tubes also have some serious disadvantages that may limit their use as part of an automatic tire contact pressure-detection system. They are not well suited to high traffic volume conditions. Tests have shown that pneumatic tubes placed side-by-side in the same lane can produce counts that vary by as much as 30 percent over a 15-min time interval. The tubes also tend to work loose under heavy traffic, reducing the accuracy of the critical actuation time measurements needed to compute vehicle speed and tire contact area.

Tapeswitches

Tapeswitches are generally used in temporary applications but can be installed permanently. These sensors are basically long, narrow pairs of metallic contacts separated along their edges by insulation. The device is protected from environmental conditions by a waterproof vinyl sheath.

The cost of each tapeswitch ranges from approximately $30 to $100, depending on the type of construction. The less expensive type consists essentially of the sensing element with its protective covering. The more expensive type adds a rigid steel frame to provide durability.

Tapeswitches are usually affixed to the highway surface with adhesives. The adhesives that have been used for this purpose vary widely and include tape with adhesive material on two sides, cloth impregnated with rubberized asphalt, and masking tape.

The basic tapeswitches are less than $^3/_{16}$ in. high and are not particularly conspicuous to drivers. However, the addition of the steel frame increases the profile to $^7/_{16}$ in., which makes it much more conspicuous. They are more accurate than pneumatic tubes, due principally to the fact that they can be securely fastened to the surface of the roadway. The closure of the switch is also more reliable than the operation of the diaphragm in the pneumatic tube sensor.

Piezoelectric Cable

Piezoelectric cable operates on the principle that electrical charge is generated when certain crystalline materials are subjected to stress. One type commonly in use now is a coaxial cable with crystalline piezoelectric powder as the dielectric material. Both temporary and permanent installations of this sensor have been successfully made. As an axle sensor, piezoelectric cable has the advantage that it, like the tapeswitch, can be exactly placed to provide the level of accuracy for actuation measurements needed in determining tire contact pressure.

Piezoelectric cable also has one significant advantage over other axle sensors for use in measuring tire contact area. That is, the magnitude of the signal produced by the cable is proportional to the pressure applied to it. This sensor is therefore able to detect whether a single or dual tire has caused the actuation. For example, Figure 13 shows the general form for the signals produced by single and dual tires passing over a piezoelectric cable axle sensor placed diagonally across the right wheel path of a traffic lane.

Triboelectric Cable

Triboelectric cable is coaxial cable that produces an electrical charge on its conductive surface because of friction between its constituent materials when subjected to stress. Commonly available commercial and industrial types of coaxial cable exhibit this property when subjected to vibration or flexure. For permanent installations, the cable is usually encased in epoxy or polyurethane and placed in a slot in the pavement, which is then sealed. For temporary applications the cable is used similarly to the piezoelectric cable previously described. Its accuracy as an axle sensor is based on the accuracy with which it can be placed and maintained.

Capacitive

Capacitive axle sensors are based on the deflection of conducting surfaces caused by the passage of a wheel. The change in

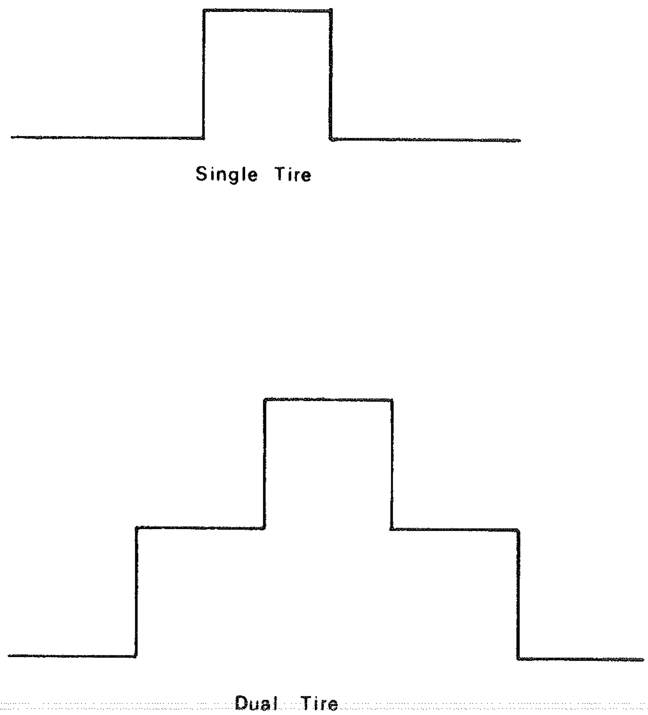

FIGURE 13 Axle detection signals produced by single and dual tires passing over piezoelectric cable.

separation of the conductive surfaces results in a change in the capacitance of the assembly. Coaxial cable can be used for this purpose in a manner similar to that described for the triboelectric cable. The principal difference in the two applications of the coaxial cable is in the signal-processing electronics.

Another form of capacitive axle sensor is the capacitive strip/mat sensor. This device has been studied and used extensively as a weight sensor and also might be used as an axle detector. However, it does not appear to offer any advantages over other technologies for this application.

WIM Systems

As indicated previously, it is necessary to acquire the weights of wheels while the truck to which they are attached moves over the tire contact pressure sensor array. A significant amount of effort has been expended and is now in progress to develop equipment and techniques for performing this function. The available commercial truck WIM equipment is described in the following paragraphs. An assessment of the likelihood of success of incorporating automatic tire contact pressure features into each WIM system is provided. In general, this feasibility depends on the ability of a system to accurately measure the wheel loads on one side of an axle.

Radian Corporation

The Radian Corporation WIM system has been in use by the Department since 1974. It consists of an independent weight transducer in each wheelpath. The weight sensors provide both weight and axle sensor functions. This system is appropriate for inclusion of a tire contact pressure feature in the configuration described in the previous section. That is, only a single diagonal axle sensor needs to be added to the sensor array (see Figure 7). The software could then be modified to make the necessary calculations and store the data. More detail about this process is included in the following sections.

Streeter Richardson

The Streeter Richardson Division of the Mangood Corporation produces two different types of WIM system: one permanent and one portable. The permanent unit has one weighing platform in each wheel path. Speed data are provided by two inductive loops. Both truck weight and axle-sensing functions are provided by the weighing platform. This equipment is adaptable to truck-tire contact pressure measurement by the addition of a diagonal axle sensor in exactly the same way as that described for the Radian system, shown in Figure 7. This equipment is not easily moved between sites and generally stays where it is installed.

The Streeter Richardson portable WIM system uses a capacitive weighmat with two inductive loops for measuring speed. This equipment is also usable for measuring truck tire contact pressure by the addition of a diagonal axle sensor following modification similar to that described for the Radian WIM system. However, there is only one weight sensor and it is in the right wheel path. Consequently, only tire contact pressures for the right side tires can be obtained.

International Road Dynamics

Conceptually, the IRD WIM system is similar to both the Radian and Streeter Richardson permanent systems in that there is a weight sensor in each wheel path that also serves as an axle sensor for computing the distance between axles. Speed information is provided by inductive loops. Adaptation of this equipment to tire contact pressure measurement can be accomplished by the addition of a diagonal axle sensor, as shown in Figure 7, and software to process the data.

Golden River Corporation

The Golden River Corporation markets a portable WIM system that uses the same sensor configuration as the Streeter Richardson portable WIM equipment. The principal difference in the two systems is that Streeter Richardson uses a Compaq portable microcomputer as the central processing component, whereas Golden River uses a dedicated microprocessor-based data collection system. Modification of this equipment to measure tire contact pressure is feasible in a manner similar to the Streeter Richardson portable system.

Siemens-Allis (PAT)

The Siemens-Allis (PAT) WIM system has wheel load sensors in each wheel path. Speed measurement is provided either by inductive loops or by two wheel load weighers, longitudinally spaced. This equipment can be modified for measuring tire contact pressure by the adjustments previously described for the other permanently installed WIM systems.

Bridge Weighing Systems

The Bridge Weighing System does not weigh individual wheel or axles directly. The wheel loads must be mathematically derived and users have had difficulty in obtaining acceptable levels of wheel weight accuracy with this equipment. This WIM system does not seem appropriate for measuring tire contact pressure in its current state.

Weighwrite

The WIM system offered by the Weighwrite Company operates only at very low speeds and weighs all tires on an axle simultaneously. Consequently, individual wheel load data are not available and this equipment is not appropriate for measuring tire contact pressure.

TIRE CONTACT PRESSURE MEASUREMENT SYSTEMS

The following discussion presents two conceptual configurations for measuring tire contact pressure automatically.

Option 1: Existing WIM Equipment with Tire Footprint Measurement

WIM equipment is widely used in the United States and is being implemented on an increasingly larger scale. It is therefore very attractive to use these existing devices for the measurement of tire contact pressure. Given that the WIM equipment will produce wheel loads, this option will require the addition of tire contact area sensors with a means of combining the WIM data with the tire contact area data for the calculation of tire contact tire pressure.

The department now uses two different WIM systems for the collection of truck weight data. The first of these is the Radian Corporation WIM system, which uses weight sensors incorporating strain-gauge load cells in combination with an IBM-XT microcomputer equipped with interface and signal processing electronics. The weight sensors are placed in prepared shallow excavations for each session of truck weighing. The microcomputer is housed within a van that has been modified for on-site truck weighing. In addition to the truck weight sensors, a pair of inductive loops is provided for each lane. These loops provide presence signals that are used for calculating speed and for activating the electronic subsystems of the truck weighing system.

The use of the IBM-XT microcomputer within this system contributes to the ease of this modification, because this equipment is generally easier to work with than the proprietary dedicated electronics formerly used in the system. As indicated in the previous discussion and in Figure 7, the only modification needed for the existing Radian WIM sensor array is a diagonal axle sensor. This device provides information about sensor width that is used with data already acquired by the WIM system (wheel weight and footprint length) to calculate tire contact pressure according to the relationship

$$P = W/A$$

where

P = the tire contact pressure in psi,
W = the wheel weight in pounds, and
A = the tire contact area in square inches.

As a part of this feasibility study, the Texas Transportation Institute (TTI) conducted limited tests to determine the best angle for the diagonal cable. The results of this activity showed that angles of less than 30° with the lateral dimension of the traffic lane could result in interference with the measuring process because of the nearly simultaneous production of signals by tires on opposite ends of the same axle. Angles of greater than 60° are difficult to use when the tires on both ends of an axle need to be measured. Limited tests of piezoelectric cable and other axle sensors confirmed that the piezoelectric cable should be considered for use as the diagonal axle sensor because of its ability to distinguish between single and dual tires on a wheel. The software required for this task can be obtained either by modifying the existing WIM system software so that the appropriate calculations can be made and the data elements (P and A) are stored with each record as it is acquired; or modifying the software used to process the data after they are collected.

Either approach will produce the needed results. The choice of the approach will depend on the availability of personnel familiar with the WIM system software and the economic constraints. The modification of the WIM system has, however, proven to be difficult in the past because of the reluctance of vendors to provide the source code and support required for the user or a hired consultant to effectively perform this task. At the same time, the vendors have generally had little interest in making changes to the software or hardware without significant charges. The best solution is therefore the second one, in which information output by the WIM system is used in conjunction with axle sensor actuation data to calculate tire contact pressures during the processing of the data at the end of a study—not during the data collection.

If the data necessary for calculating tire footprint length are not available but the outputs of vehicle speed and wheel load can be obtained from the WIM system, the configuration shown in Figure 2 can be used to acquire tire contact area for use in computing the tire contact pressure. Because the weight-sensor actuation data are not available in this case, it is unlikely that the software will be available for modification. It will therefore be necessary to compute tire contact pressure from the individual data elements at the data-processing stage.

Option 2: Direct Measurement of Tire Contact Pressure

As indicated earlier, pressure-sensitive materials exist that could be used in the development of a stand-alone tire contact pressure system without the addition of the output from a WIM system. Two approaches are described in this discussion. One uses piezoelectric film and the other uses piezoelectric cable.

As a part of this feasibility study and other research, TTI conducted limited tests on piezoelectric film to determine its suitability for use in a tire contact pressure detector. Previous research had focused on the use of the pyroelectric characteristics of the material as a passive infrared vehicle sensor. That work demonstrated that the material was very sensitive to electrical noise and vibration so that it was not suitable as an infrared vehicle sensor without an extended research and development program. The application of the material to direct measurement of tire contact pressure presents similar problems that must be overcome. The direct pressure caused by the tire and sensed by the piezoelectric film must be isolated from electrical noise, vibration, and infrared energy. Fortunately, it is much easier to accomplish these tasks in the context of an enclosed mat than with an exposed element of film.

Another difficulty that must be overcome with the film is the lack of uniform sensitivity to pressure for the manufactured product. Areas of the same roll can vary by as much as 10 percent in sensitivity to pressure. The pattern of pressure-sensitive elements shown in Figure 9 was developed by TTI in order to offset this effect. By cutting the material into 1-in. squares, it is possible to measure the sensitivity of each square and sort the squares into groups of the same sensitivity. TTI has developed a method for testing large numbers of these elements quickly and efficiently. Squares with the same sensitivity are then used to make a tire contact pressure sensor using the pattern shown in Figure 9. In this application, the elements are each monitored to determine the magnitude of the signal being generated by tire contact pressure. This process can provide not only the average tire contact pressure but also a measure of the variation of the pressure across the tire contact area.

A microcomputer with interface and signal processing hardware and software are necessary to complete the system.

Research is now underway to assess the feasibility of using piezoelectric cable as a weight sensor. If this effort is successful, the resulting system could provide tire contact pressure data by installing three sections of the cable in a configuration similar to that shown in Figure 2.

CONCLUSIONS AND RECOMMENDATIONS

It is both feasible and desirable to acquire tire contact pressure data automatically. It appears that a quick implementation of this concept can be realized by adding one diagonal axle sensor to the Department's portable and permanent WIM systems. Both portable and permanent types of axle sensors are available. Direct measurement of truck tire contact pressure is also possible but will require additional research and development.

The availability of automatically acquired truck tire pressure data will allow for making policy decisions about the modification of the Department's pavement design procedures to take into account changing tire inflation pressures.

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Publication of this paper sponsored by Task Force on Weigh-in-Motion.