Photoelectric Sensors for Counting and Classifying Vehicles

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Modern photoelectric sensors usually consist of a light emitting diode (LED) source and a phototransistor receiver with associated lenses and electronic signal-processing circuits. The LEDs are operated in the infrared wavelengths for efficiency, and are pulse modulated to overcome the adverse effects of ambient light, slight misalignment, and partial obstruction of the beam. These devices are packaged in small, moisture-resistant housings and are readily available, commercially. Photoelectric sensors mounted above, beside, or on the roadway surface can detect the presence of vehicle bodies and tires. A pair of sensors produces the information needed for calculating vehicle speed, direction of travel, overall vehicle length, and axle spacing. An array of three sensors produces information for determining single or dual tires and the lateral position of the tires in the traffic lane. The three-sensor array also makes it possible to estimate the size of the tire-pavement contact patch. Attempts to correlate these measurements with wheel loads and gross vehicle weights have not yielded satisfactory results. However, for many traffic survey applications, reflex-type infrared sensors offer an economical and practical alternative to other types of vehicle and tire sensors, especially for short periods of time. They are commercially available, relatively inexpensive, durable, produce output signals compatible with most traffic recording devices, and can be installed without cutting the pavement surface.

Traffic data are the fundamental basis for planning, designing, constructing, operating, maintaining, and managing the vast street and highway system that serves the transportation needs of the nation. Without sufficient traffic data, none of these functions can be performed properly. Acquiring and using traffic data in a timely and effective manner is, therefore, an important responsibility for the transportation profession. Basic data needs consist of vehicle volume counts, classes of vehicles composing the traffic stream, speed, and weight. For counting vehicles and measuring their speed, technologies that simply detect the presence or absence of the vehicle, or its axles, at a point with respect to time are used. Classification is normally accomplished by counting the number of axles per vehicle, and sometimes criteria of single or dual tires on a wheel assembly, axle spacing, or axle group configuration are included in the classification scheme. Vehicle weight data consist of information about wheel loads, axle loads, axle group loads, and gross vehicle weight. These data are obtained either by static weighing or by weigh-in-motion (WIM) techniques.

Various types of sensors have been developed and used for acquiring traffic data over the years. The more common types of sensors for detecting the presence of a tire or a wheel assembly include the pneumatic tube with a diaphragm at the end, a pressure treadle, a piezoelectric cable or strip, and a capacitance strip. Vehicle presence or passage is usually detected by a device such as an inductance loop, or ultrasonic, magnetic, or radar detector. Loads and weight of a static vehicle are measured by a vehicle scale, an axle-load scale, a portable axle-load weigher, or a wheel-load weigher. WIM sensors consist of load cell, bending-plate, or capacitance mat tire force sensors; piezoelectric or capacitance change pressure-sensing strips; or strain-gaged structures such as bridges or box culverts.

Light beam sensing using incandescent lamps and photocells, with the associated problems of bulb burnout, sophisticated lenses, inadequate light energy, large power consumption, adverse effects of ambient light, and critical alignment, was used with only limited success for sensing vehicles before light emitting diodes (LEDs) were introduced in the 1970s. Availability of efficient LEDs, phototransistors, and digital signal-processing computers since that time has made it possible to overcome many of these problems. Research into applying commercially available photoelectric sensors and microprocessors for counting, classifying, and weighing highway vehicles is described.

HOW PHOTOELECTRIC SENSORS WORK

Every photoelectric sensor has two basic parts—the transmitter, usually an LED, and the receiver, usually a phototransistor. An LED is a solid-state semiconductor that emits light when electric current flows through it in the forward direction. It can be switched on and off very rapidly (pulse-modulation), is not sensitive to vibration, can handle a wide range of temperatures, and will last virtually forever. LEDs that emit visible red, green, or yellow light are quite familiar as indicator lights on electronic instruments, but other LEDs emit in the infrared (IR) wavelengths. IR emission has wavelengths longer than about 800 nm. Visible red LEDs operate in the range of 600 to 700 nm. IR LEDs emit at higher intensity than visible red LEDs, have higher optical penetrating power, and are the best spectral match to most phototransistors; therefore, they are preferred for some applications. Both visible red and IR LEDs were used in the research. Modulating the light emitted from the LED transmitter at a particular pulse frequency and then tuning the phototransistor and its amplifier to amplify only this frequency makes it possible to eliminate the adverse effects of ambient light, partial obstruction of the light beam, and slight misalignment (1,2). This consideration is critical in sensing vehicles operating day and night under a wide variety of climatic conditions. Lens systems

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direct and focus the emitted light and the received light into the most effective patterns for each particular application.

These optical systems are designed for one of three sensor operating modes: through-beam sensing, reflex sensing, or proximity sensing (3). In the through-beam mode, the modulated light beam from the transmitter to the directly opposed receiver is normally uninterrupted. When the beam is interrupted by an opaque object, the output signal from the receiver changes. This mode affords the maximum sensing range and is not affected by reflections from the surface of objects being detected. In the reflex mode, the transmitter and receiver are set side by side, and the light beam is aimed at a retroreflector, which sends it back to the receiver. The output from the receiver changes when the beam is interrupted. In this mode, there is some loss of light in the retroreflector, the sensing range is about half that for the through-beam mode, and reflections from objects in the path of the beam can cause false detections. In the proximity mode, the transmitted beam is aimed in the direction of the potential target object, as is the receiver. When the beam is reflected from the surface of the object and detected by the receiver, the output signal changes. This mode depends upon the reflectivity of the object and is generally not suited for vehicle detection.

Response time (light-to-dark or dark-to-light transition) for photoelectric sensors is generally in the range of thousandths to millionths of a second. This is the maximum time after the transition occurs until the output switch from the photoelectric sensor changes its on-or-off condition. Of course, electronic circuits can be used to delay or extend the change time if desired. For certain types of vehicle-sensing operations, very short response time is important.

SENSOR POSITIONS

For counting, classifying, or weighing highway vehicles, the infrared sensors are mounted beside or above the traffic lane with the modulated light beam directed in such a way that either the tires or the body of a passing vehicle will block the beam. Different sensor positions are shown in Figure 1. Sensor S1 is a reflex type and is mounted overhead with the transmitted light beam aimed straight down at Retroreflector R1 on the pavement surface. Sensors S2 and S3 are positioned adjacent to the lane at heights that allow the light beam to
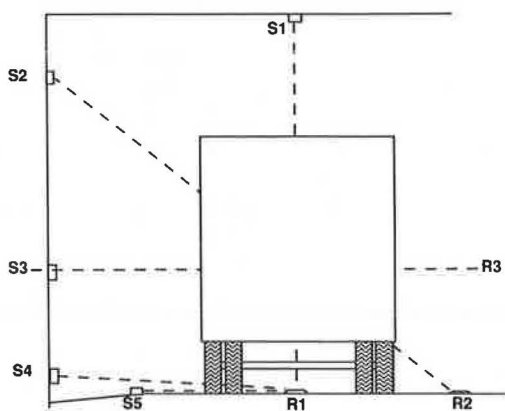

FIGURE 1 Sensor, receiver, and reflector mounting positions.

sense the presence of a vehicle body. Sensor S2 is a reflex type working off Retroreflector R2, which is mounted at the far edge of the lane on the pavement surface, or somewhat above it for a single-lane roadway such as a ramp. Sensor S3 can be either through-beam or reflex type. In the through-beam mode, the transmitter in Sensor S3 is paired with a separated receiver, R3, which is usually connected with the sensor by a hard wire. In the reflex mode, R3 represents a retroreflector that sends the transmitted light beam back to a receiver mounted beside the transmitter in the sensor head. Sensors S4 and S5 are the reflex type and are used to detect the presence of a wheel in the right-hand side of the traffic lane. Retroreflector R1 is mounted on the pavement surface near the center of the lane with the reflective axis aligned with the transmitted beam. Sensor S4 is mounted laterally in a position off the edge of the lane—perhaps behind a curb or beyond the shoulder—with the light beam aimed somewhat above the pavement surface. Sensor S5 is positioned at the right-hand edge of the lane with the light beam very close to the pavement surface.

Overhead Mounting

For counting vehicles, the sensor can be placed in the overhead position on a structure such as a mast arm or overpass bridge and aimed downward, perhaps at a small angle, at a retroreflector on the pavement surface in the center of a traffic lane. Whenever a vehicle body breaks the beam, a signal is sent to the counter. Trailers with long, slender tongues might be counted as separate vehicles, particularly at slow speeds, unless a time extension is used with the signal. Selecting an appropriate time extension is problematic if high-speed vehicles operate at very short headways at the site.

The retroreflectors on the pavement surface must be sturdy because tires will occasionally run over them. Hollow plastic corner-cube retroreflectors, 3 in. in diameter—sometimes used as delineators—secured to the pavement surface with epoxy and surrounded by two layers of asphalt roofing shingles in annular rings have functioned for several weeks under heavy freeway traffic before being crushed. Similarly, reflective sheeting (encapsulated beads and microcubes) on a thin metal plate has performed well for a few weeks, except when a film of water was present on the surface of the sheeting. A 6-in.-diameter array of small-diameter ($\frac{3}{4}$ to 1 in.) plastic retroreflectors attached to a thin metal plate with, and surrounded by, epoxy is now being tested. The rationale for testing this arrangement is that the short spans across these hollow plastic structures will be able to resist the tire forces better without crushing. Also, for maximum effectiveness, the size of the reflector array can be made the same as that of the light beam at the particular distance from the transmitting lens for each site. The reflector assemblies are prepared for installation by applying epoxy to the bottom of the reflector and cut-back asphalt to the bottom surface of the surrounding roofing-material rings at the roadside. A short piece of duct tape is also attached to the top surface at one edge of the assembly with overhanging ends. The assembly can be placed in the center of the traffic lane in about 10 sec. The duct tape prevents movement of the assembly until the epoxy and asphalt cure within a few minutes.

Two overhead sensors, with companion retroreflectors, mounted a fixed distance apart along the lane in the direction of traffic flow makes it possible to count vehicles, measure their speed and overall length, and classify them according to speed and length. A sensor-separation distance of 2 to 3 ft has been found to be quite adequate. Data can be obtained for each lane of a multilane facility.

Roadside Mounting

Sensors may be mounted beside the traffic lane with the light beams aimed to detect the presence of a vehicle body, chassis, or load. The size, shape, and vertical position of these vehicle components vary widely; therefore, it is difficult—perhaps impossible—to find a unique location for a single light beam directed across the lane to detect every vehicle.

When the sensor is mounted beside the lane and aimed downward toward a reflector at the far edge of the lane, as shown by *S2* and *R2* in Figure 1, the light beam should have an angle of about 35 to 45 degrees upward from the pavement surface to detect passenger cars as well as trucks with trailer frames 4 ft or more above the pavement. The retroreflector must be mounted so that its reflective axis is approximately coincident with the alignment axis of the transmitted light beam. Two, or more, sensors at different heights can be connected (by a logical OR circuit) so that interruption of any light beam causes an output signal. This lane-side position allows detection of vehicles only in the lane adjacent to the sensor (usually the right-hand lane or the median lane on a multilane road).

A similar sensor mounting is shown by *S3* and *R3* in Figure 1, but the receiver or the retroreflector is mounted at some height above the pavement surface to accommodate a more-or-less horizontal light beam. This arrangement is best suited for sensing vehicles in single lanes such as ramps, turning roadways, or authorized-vehicle lanes. If the error in vehicle count caused by simultaneously arriving vehicles interrupting the beam is not considered to be significant or is recognized in data analysis, it can also be used to count vehicles on multilane roadways. The OR logic can also be used with multiple sensors positioned at different heights with one or more receivers or reflectors mounted beyond the far lane edge and above the pavement surface to enlarge the detection zone in three-dimensional space.

A pair of sensor arrays of this type set a fixed distance apart along the lane in the direction of traffic flow can be used to count vehicles, to measure their speed and overall length, and to classify them according to speed and length. The pair of sensors also makes it feasible to detect the direction of movement for each vehicle.

Pavement Level Mounting

Sensors located at the edge of the traffic lane, on the shoulder, or beyond, with the light beam aimed just above the pavement surface can detect the presence of a tire. This arrangement is shown as *S4*, *S5*, and *R1* in Figure 1. For counting axles, a single light beam at right angles to the direction of traffic flow is adequate. Two such beams a known distance apart longitudinally can be used to measure speed.

Field experience has indicated that a conventional 4 × 4-in. white retroreflective raised pavement marker in the center of the lane is easy to install, has sufficient reflectance, and functions for at least several weeks. The 4-in. width of the reflector poses no problems for counting and measuring speed, but a narrow beam is desirable when the time of interruption is used to measure tire-pavement contact length and width. Small, round reflectors (of $\frac{3}{4}$- to $\frac{7}{8}$-in. diameter)—like those used in reflectorized letters on highway signs—reflect a narrower light beam, but when mounted vertically and recessed about $\frac{1}{4}$ in. into the side of a protective, cast-aluminum housing have exhibited drastically reduced reflectivity after 2 or 3 days of freeway traffic because of tire marks or an accumulation of road film on the plastic surface. Simply cleaning the surface of the reflector has restored off-shoulder reflex sensors to operation. This experience indicates that surface-mounted reflectors of this type are suitable for data collection sessions involving tire sensing that last for only a few days or weeks. Adequate reflectivity for longer periods—perhaps a few months—can be achieved by using conventional retroreflective raised pavement markers.

Reflex sensors located just beyond the shoulder (see *S4* in Figure 1) have functioned for 8 weeks and are still operational at the time of this writing. Protective tubes 1.5 in. in inside diameter and 4 in. long in front of the sensor lenses deflect rain, dust, and spatter. This location allows the sensors to operate much longer than those on the edge line of the lane (see *S5* in Figure 1). As described earlier for the small retroreflectors, lenses of the miniature reflex sensors that were mounted on the edge line in special cast-aluminum housings resembling a raised pavement marker accumulated enough road film in 2 or 3 days to make them inoperable. More accurate measurements of tire-pavement contact area are feasible with the sensor in close proximity to a small-diameter reflector than with the off-shoulder sensor working off a raised pavement marker, but frequent—almost daily—cleaning of the lenses and reflectors is required. Even with these limitations, photoelectric sensors offer certain advantages over pneumatic tubes, tape switches, piezoelectric or inductance strips, and pressure treadles for tire and axle detection in certain situations.

APPLICATIONS

Photoelectric sensors can be arranged to detect the presence or absence of a vehicle tire or of a vehicle body, chassis, or load with respect to time and location in space. Thus, vehicles or axles can be counted, vehicle speed can be measured, the number of axles per vehicle can be determined, spacing between successive axles on a moving vehicle can be calculated, single or dual tires can be distinguished, the approximate size of the tire-pavement contact area can be estimated, and the overall dimensions (length, width, and height) of the moving vehicle body can be calculated.

Counting

A single modulated light beam, or an array of beams, can be used to count the number of times that the beams are broken

by an object. The object might be a vehicle tire or a vehicle body, chassis, or load. Figure 2 shows a comparison between the number of axles counted in the right-hand lane of IH-35 during five 15-min periods by three different sensing techniques: an infrared reflex sensor mounted off the shoulder and aimed at a retroreflective raised pavement marker, a piezoelectric cable, and three human observers. Counts by the three human observers never agreed; therefore, a mean value is shown. Variation in the manual counts ranged from two to seven axles during a 15-min period. Some of this variation was probably caused by the fact that a few vehicles changed lanes near the sensing site. In four of the five counting periods, the piezoelectric cable gave the lowest count.

Speed

The output signals from two or more modulated light beams, or arrays of such beams, separated by a known distance and aimed across the path of a moving vehicle can be used to measure the travel time of the vehicle between the beams. The distance between the beams divided by the time is the average speed of the vehicle. Appropriate accuracy of speed measurements can be attained even though the spacing between the two beams is quite short, e.g., 2 or 3 ft, as the response time of photoelectric sensors is almost instantaneous and of similar magnitude for two sensors of the same type.

Most WIM systems measure vehicle speed and calculate axle spacing along with wheel loads and gross vehicle weight. A pair of photoelectric sensors mounted on the pavement surface in advance of the instrumented structure has been used in conjunction with a bridge research study to detect approaching vehicles and indicate their speed, axle spacing, and lane of operation (Jeff Schulz, unpublished data). In fact, David Huft's use of modern photoelectric sensors in this way for development of the South Dakota bridge WIM system suggested this application several years ago.
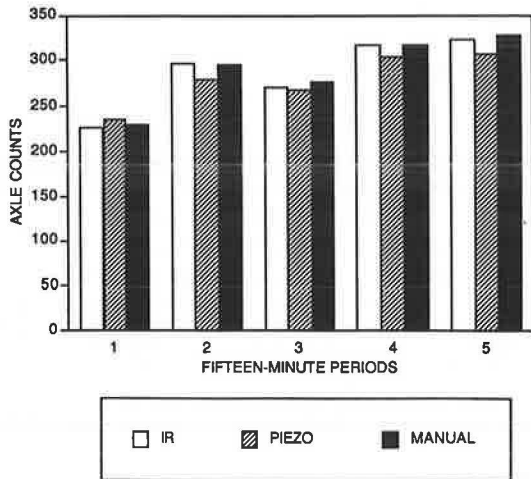

FIGURE 2   Comparison of IR, piezo-cable, and manual count of axles.

Vehicle Classification

Vehicles are frequently classified according to the number of axles per vehicle, axle spacing or arrangement (single, tandem, triple, etc.), single or dual tires, or overall vehicle length or height. To apply any of these criteria, the presence of an individual vehicle must first be determined. Then, measurements of the various factors pertaining to the vehicle can be made. Photoelectric sensors can be used to determine both vehicle presence and tire or axle presence, but a practical combination of sensors for classification is to use an inductance loop detector for vehicle presence and photoelectric sensors for detecting tires.

The arrangement of three pavement-level photoelectric sensors plus an inductance loop detector shown in Figure 3 yields information for classifying vehicles according to speed, axle spacing, single or dual tires, overall vehicle length, wheelbase, or lateral position within the lane. The time relationship among signals from these four sensors resulting from a two-axle, single-unit, six-tired vehicle is shown schematically in Figure 4. Speed is calculated as the distance between $S1$ and $S3$ divided by time, tv. Axle spacing is time, ta, multiplied by speed. Tire-pavement contact patch length is time, tl, multiplied by speed. Single or dual tires are indicated by the relative duration, tw, of the beam interruption at Location $S2$, assuming that the front tire is a single. Or, alternatively,
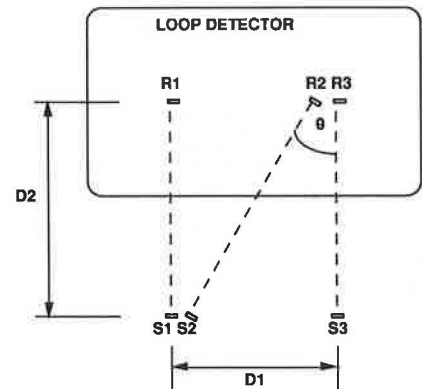

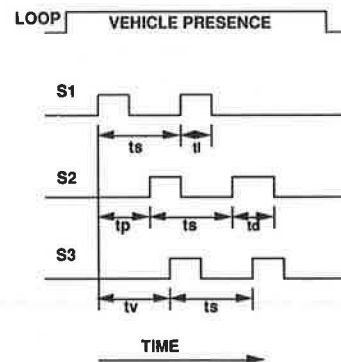FIGURE 3   Arrangement of pavement height sensors.

FIGURE 4   Time relationship among signals from sensors.

overall tire width can be calculated. The length of the tire-pavement contact patch is represented schematically in Figure 5 as Ls for a single-tire length and as Ld for dual tires. The diagonal dimensions of the respective tire-contact patches of single and dual tires are shown as DDs and DDd. The projection of these dimensions, $PDDs$ and $PDDd$, are measured as the time of interruption of $S2$, which is the diagonal light beam. The overall width of the tires is calculated as a function of tire length, projected diagonal dimension, and vehicle speed. Overall vehicle length is determined by multiplying the time that the loop detector is occupied times speed and subtracting the length of the loop. Wheelbase is the total time between the frontmost and rearmost tires on the vehicle, or vehicle combination, crossing $S2$ multiplied by speed. Lateral position within the lane is calculated as a function of the tire's travel time, tp, between $S1$ and $S2$, knowing speed.

IR light beams have been used in North Carolina, Louisiana, and Mississippi to detect overheight vehicles approaching overhead structures and warn drivers of impending danger (4). For these applications, through-beam sensors are mounted several feet above the road surface, and contamination of the lens surfaces seems to cause no significant problem. Pairs of pavement level IR beams are currently being evaluated for classifying vehicles according to single or dual tires and the number of axles per vehicle in conjunction with auditing toll collection operations in Oklahoma.

Weight

The size of the tire-pavement contact patch is an indication of the load on the tire. For any given tire, the more the load, the larger the contact patch. Many factors affect this relationship, however. For example, tire inflation pressure, temperature, size, ply material and arrangement, tread material and pattern, as well as vehicle speed and dynamic behavior all interact to determine the properties of the patch. Only a crude relationship between tire load and tire-pavement contact patch size can be expected.

In order to determine whether a useful relationship could be developed, an array of photoelectric sensors and an inductance loop detector were arranged directly above the right-hand wheel force transducer of a Radian WIM system, and data from both systems were recorded simultaneously. The
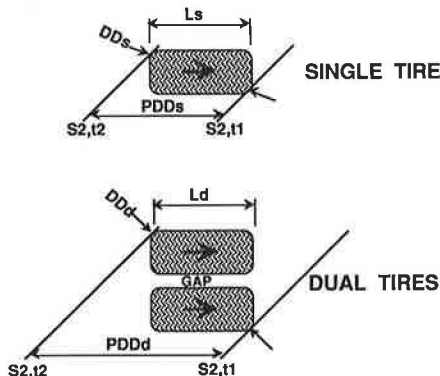
site was at a rural location near Junction, Texas, on IH-10 where traffic was traveling at high speed. Data from 149 five-axle tractor-semitrailer trucks are shown in Figure 6. The values shown are measurements of individual right-side tires summed for the five axles on each truck. A straight line of best fit to the data points is shown. A cluster of points near the lower left corner of this figure representing right-side vehicle weights less than about 15,000 lb (gross vehicle weights less than about 30,000 lb) is probably associated with empty trucks. There appears to be a trend of increasing tire length with increasing wheel load, but the large amount of scatter in the data makes meaningful weight estimation from measurements of tire-pavement contact patch length impracticable. No better relationship between wheel load and other tire-pavement contact patch characteristics such as width or area could be discovered. Size of the tire-pavement contact patch alone seems to be an inadequate indicator of tire load for mixed vehicle types.

CONCLUSION

Photoelectric sensors can be mounted above or beside a roadway and used to detect the presence of a vehicle tire, body, chassis, or load. This information is the basis for essential traffic survey data concerning speed, volume, classes of vehicles in the traffic stream, and structural loading of pavements and bridges. Field studies indicate that roadside-mounted reflex pulse-modulated IR sensors working off retroreflective raised pavement markers in the middle of the lane can be used successfully to sense vehicle tires for periods of several weeks. Two or more through-beam or reflex sensors connected in a logical OR mode and aimed to intercept the vehicle body, chassis, or load are suggested for detecting the presence of a vehicle. Pairs of photoelectric sensors separated a known distance produce the information needed to calculate vehicle speed, direction of travel, overall length, and axle spacing. A three-sensor array can additionally indicate single or dual tires and lateral position of the wheel in the lane. In many cases, reflex-type IR sensors offer an economical and practical alternative to pneumatic tube, piezoelectric or inductance strip, and pressure-treadle axle detectors, and to inductance loop, ultrasonic, magnetic, and radar vehicle detectors, especially for temporary traffic sensing applications. IR photoelectric
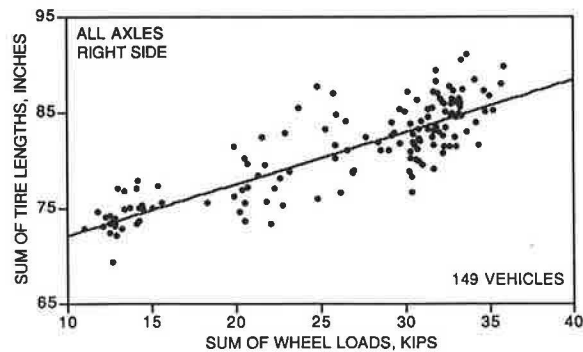
FIGURE 5 Length and projected diagonal dimension of single and dual tires.

FIGURE 6 Photoelectric sensor tire length versus WIM wheel load.

sensors are commercially available, relatively inexpensive, produce output signals that are compatible with most traffic recording devices, durable, and can be installed without cutting the pavement surface.

ACKNOWLEDGMENT

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