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16. Abstract

This study evaluated the applicability, durability, and accuracy of two general systems of sensors that were used to monitor truck speeds on a freeway connector: 1) pavement sensors mounted on the surface or submerged into the pavement, and 2) roadside sensors using an infrared beam technology. Pavement sensors were predominantly temporary piezoelectric sensors, although inductive loops complemented one set of piezo sensors. These pavement sensors generated signals that were processed by vehicle classifiers to produce either "binned" data or "raw" data for all vehicles using the monitored roadway. Roadside sensors monitored vehicles that exceeded a preset height, length, and speed. Findings indicate that temporary piezo sensors are accurate for use as speed, count, and classification studies, but their service life (durability) was highly variable and undesirably short in many cases. Installation and maintenance of these sensors were problematic due to interference with traffic. Infrared sensors, on the other hand, were less intrusive to the traffic stream during installation and maintenance, and they performed well with little maintenance for time periods of one year or longer.

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EVALUATION OF SENSORS FOR MONITORING TRUCK SPEEDS

by

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Assistant Research Engineer

Research Report 1232-21
Research Study Number 0-1232
Research Study Title: Evaluation of Sensors for Monitoring Truck Speeds

Sponsored by the
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IMPLEMENTATION STATEMENT

Findings of this research indicate that temporary piezoelectric sensors, when used on the surface of the roadway, are suitable for short-term axle sensors. Results show that when the temporary sensors are used for vehicle speed and/or classification, their accuracy is sufficient for conducting speed studies to evaluate the effects of traffic control treatments. Using sample sizes of 30 or more, sample means from the temporary piezos are within one mph (1.61 km/h) of radar sample means. Two significant problems exist with these sensors when used on the surface of the roadway under high traffic volumes and significant numbers of trucks and in locations where a consistent speed-change pattern occurs. The first problem is the short, and fairly unpredictable, life of these sensors; the other is the difficulty in maintaining their position on the pavement when using only adhesives typically used for temporary installations.

The life of temporary piezo sensors under high speed traffic with approximately 10 percent trucks with no external damage was determined to range as high as several million axle load applications or as low as under half a million loads. External damage resulted from shifting in the wheel paths over time or being struck by a heavy and/or sharp object. Shifting, caused by decelerating wheel forces, was correctable if caught in time. However, a cut anywhere on the sensor or on the coaxial cable was potentially destructive. Even if the sensor continued to function in dry weather, it might become completely ineffective with moisture intrusion.

The second system of sensors evaluated in this research utilized infrared sensors. This truck speed monitoring system, including a microprocessor, other hardware components, and associated software, was developed by the Center for Transportation Research at the University of Texas at Austin. Infrared technology appears to be a candidate for continued implementation due to its non-intrusive nature (little interference with traffic), its simplicity, its relatively low cost, and its use of sensors which are not damaged by traffic.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

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SUMMARY

Monitoring systems for high center-of-gravity vehicles near hazardous curves, especially on freeway connectors, are necessary to determine existing speeds and the need for speed warning devices. Recent statistics indicate that approximately one-third of the incidents to which police responded on freeway-to-freeway connectors were attributable to excessive speed. This research is a response to the concern that existing commercially available speed monitoring systems are somewhat inadequate for applications on or near elevated structures at interchanges. There were two general types of systems included in this study. One used multiple sets of pavement sensors generating signals for interpretation by International Road Dynamics (IRD) classifiers, and the other used infrared sensors. The latter systems were designed and installed by the Center for Transportation Research (CTR) of the University of Texas at Austin.

Objectives of this research included: determining the applicability and durability of sensors for speed and classification of trucks on curved freeway ramps, determining methods to protect temporary pavement sensors, testing experimental conductive plastic inductive loops, evaluating the life of pavement sensors and roadside sensors through field tests, and comparing speeds generated from both sensor systems to a known accurate calibration tool.

Field testing of experimental conductive plastic inductive loops using a PAT classifier indicated that the loops would not "tune." Upon testing after being in the pavement for a time period of approximately two years, these loops generated readings indicating discontinuities (breaks). No attempts were made to repair or replace these sensors due to their poor signal qualities.

Comparisons of the classifier/temporary piezo (TP) sensor system and radar output indicated very close agreement. However, TP sensors exhibited an undesirably high failure rate, especially where both truck volumes and speeds were high. Considering all of the temporary sensors installed on the ramp during the 65-week study period, approximately half survived the manufacturer's estimated life of one million axle applications. Ignoring the effects of traffic volume, percent trucks, and speeds, which differ from site to site along the ramp, the desirable (design) life of these sensors should be one year or longer. Of the total thirty-one temporary piezo pavement sensors installed, only three piezo film sensors and only four piezo cable sensors lasted a year or longer.

Speed data comparisons between the CTR system and radar show improvements in speed correlations with radar as hardware improvements have occurred. The primary improvement involved changing from a two-beam to a three-beam system. In comparison to the system that used pavement sensors, installation and maintenance of the CTR system was not as intrusive to traffic, and the CTR system more accurately monitors vehicles that change lanes at the sensor locations.

In conclusion, although the accuracy of the temporary piezo sensor system was excellent for purposes of speed, classification, and count studies, the number of sensor failures was excessive. The life of these sensors must be consistently at least one year for them to be considered a viable option for this type of study.

CHAPTER 1. INTRODUCTION

BACKGROUND

Based on the activity log of the Accident Division of the City of Houston Police Department (HPD) over a three-month period, approximately one-third of the incidents to which police responded on freeway-to-freeway connectors were attributable to excessive speeds. When large trucks are involved, incidents can be catastrophic, especially when the incident occurs at an interchange where spilled loads alone can disrupt traffic for several hours. Examples of incidents which have resulted in loss of life and extensive damage to the roadway infrastructure are:

1) An ammonia truck incident in May 1976 at I-610 (West Loop) and US-59 (Southwest Freeway) interchange,
2) A propane and gravel truck collision at the SH-225 (La Porte Freeway) and I-610 interchange where a police officer died and a connector was closed for a year and a half, and
3) A truck incident on July 30, 1985 in which the driver died and disrupted traffic at the I-610 and SH-225 (La Porte Freeway) interchange for several hours.

Several treatments have been considered at various freeway-to-freeway connectors in Houston based on: accident/incident history, truck volume, incidents attributable to excessive speeds, and consensus of members of the HPD Accident Division. At the I-610 (North Loop) eastbound to US-59 (Eastex Freeway) northbound connector, the HPD tried speed enforcement by use of radar following installation of regulatory speed limits. Results of this increased enforcement activity did not reflect the desired speed reduction. Other options, which are the subject of ongoing study, required the installation of sensors of various types and configurations to monitor the effects of varied traffic warning devices. Evaluation of the sensors is the subject of this report.

OBJECTIVES

Objectives of this research included:

- Determining the applicability and durability of sensors for speed and classification of trucks on curved freeway ramps;

- Determining methods to protect temporary pavement sensors from damage by traffic and to maintain their position;

- Testing experimental conductive plastic inductive loops to determine their durability in the pavement and their potential for use with a commercially available traffic classifier;

- Evaluating the life of pavement sensors and roadside sensors through field tests; and

- Comparing speeds generated from both sensor systems to a known accurate calibration tool.

SITE INFORMATION

This ramp is located north of downtown Houston at the interchange of the I-610 (North Loop) and US-59 (Eastex Freeway). The I-610 eastbound connector to US-59 northbound is the facility that is under investigation. Figure 1-1 shows the general alignment of the ramp and its relationship to other elements of the interchange. Figure 1-2 shows the ramp and its three monitoring stations, A, B, and C; and Figure 1-3 shows an enlargement of locations A and B and their sensor configurations. Location C uses a sensor arrangement similar to location B. The connector has two lanes which narrow to one lane at its downstream end before the merge with US-59. Because of its height above natural ground level, high speeds, truck volumes, and two 12-degree horizontal curves, the connector has become a particularly troublesome location.

Speeds of trucks on the ramp generally decrease from the beginning (gore area) of the ramp to the second curve, then increase gradually along the downgrade from the second curve to the merge area on the Eastex Freeway. The initial deceleration was a significant factor in the maintenance of temporary pavement sensors which will be described in more detail later. Speed reductions by smaller vehicles are not as pronounced as for trucks. Off-peak speeds for various classes of vehicles recorded by International Road Dynamics (IRD) classifiers are shown in Table 1-1. The three vehicle functional classes in Table 1-1 are consistent with the standard Federal Highway Administration (FHWA) classification scheme. Classes 1 and 2 are motorcycles and automobiles, classes 3 through 5 are light- to medium-duty trucks, vans, and buses, and classes 6 through 13 are heavy trucks. Due to a problem with the Location A classifier on June 16, 1992, data from June 25, 1992 were used instead.

Observations of peak periods indicated that speeds were not significantly different than during off-peak periods on the ramp. During the morning hours, free-flow conditions prevailed both on the eastbound I-610 mainlanes and on the ramp. However, mainlane speeds sometimes dropped below off-peak speeds during the middle to late afternoon hours so that vehicular speeds entering the ramp were lower than during other times. This was a consideration in selection of analysis periods.

Vehicles changing lanes throughout the length of the ramp affected vehicle count and speed studies. A significant number of passenger cars and other smaller vehicles shifted from the right lane to the left lane; unfortunately, this occurred often at the monitoring stations. This lane shifting slightly reduced the accuracy of traffic classification studies using pavement sensors where no presence detection (inductive loop) was used. This was due to some vehicles hitting one sensor of a set and missing the other sensor. For example, a vehicle might hit the entry sensor in lane 1 and miss the exit sensor in lane 1. That vehicle would not be classified correctly. Only the Location A permanent sensors incorporated presence detection. Observations of traffic maneuvers on the ramp indicated that trucks were more likely than were cars to remain in the same lane.

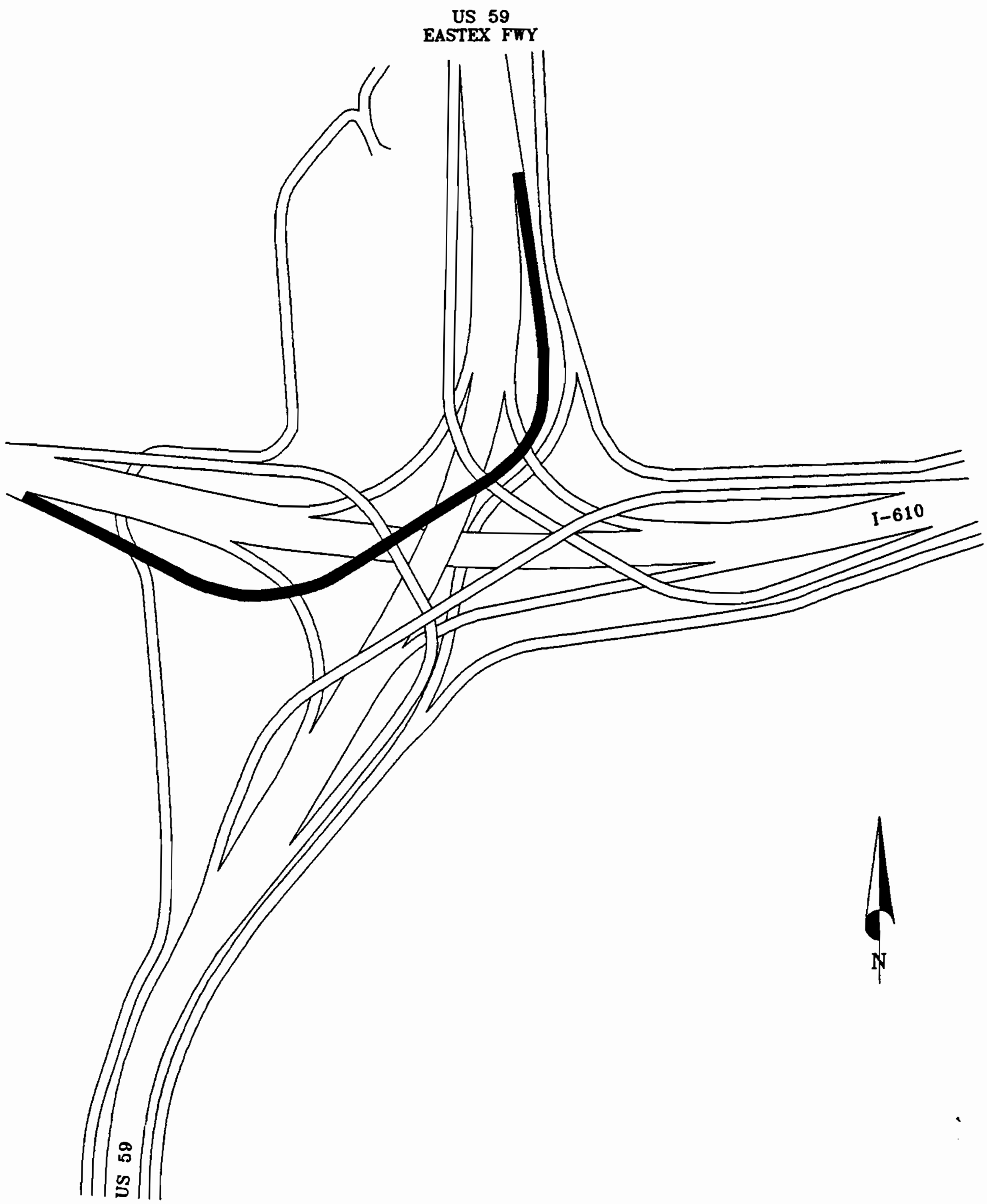


Figure 1-1. Interchange Layout Showing the I-610/US-59 Connector

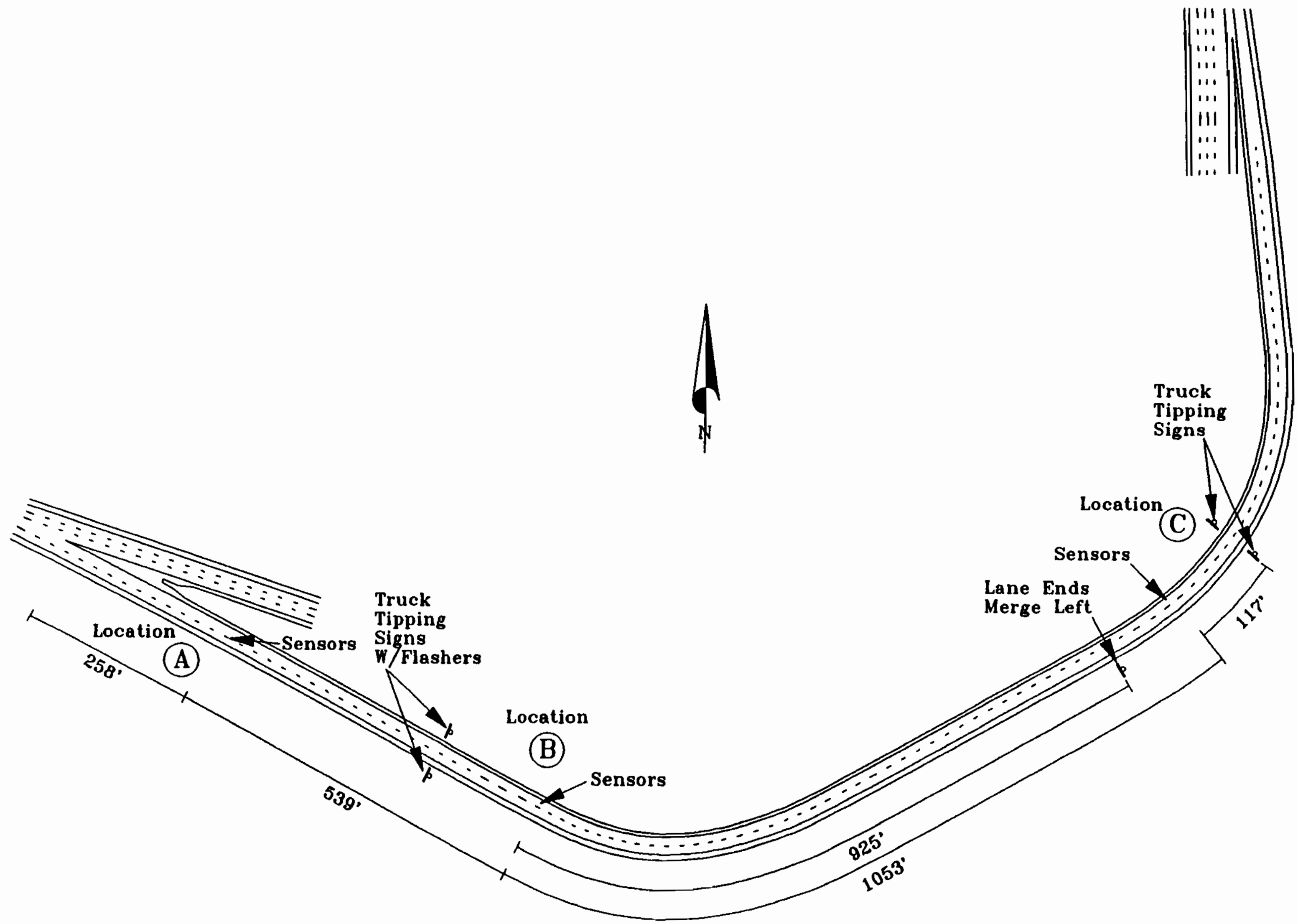


Figure 1-2. I-610 Eastbound to US-59 Northbound Connector

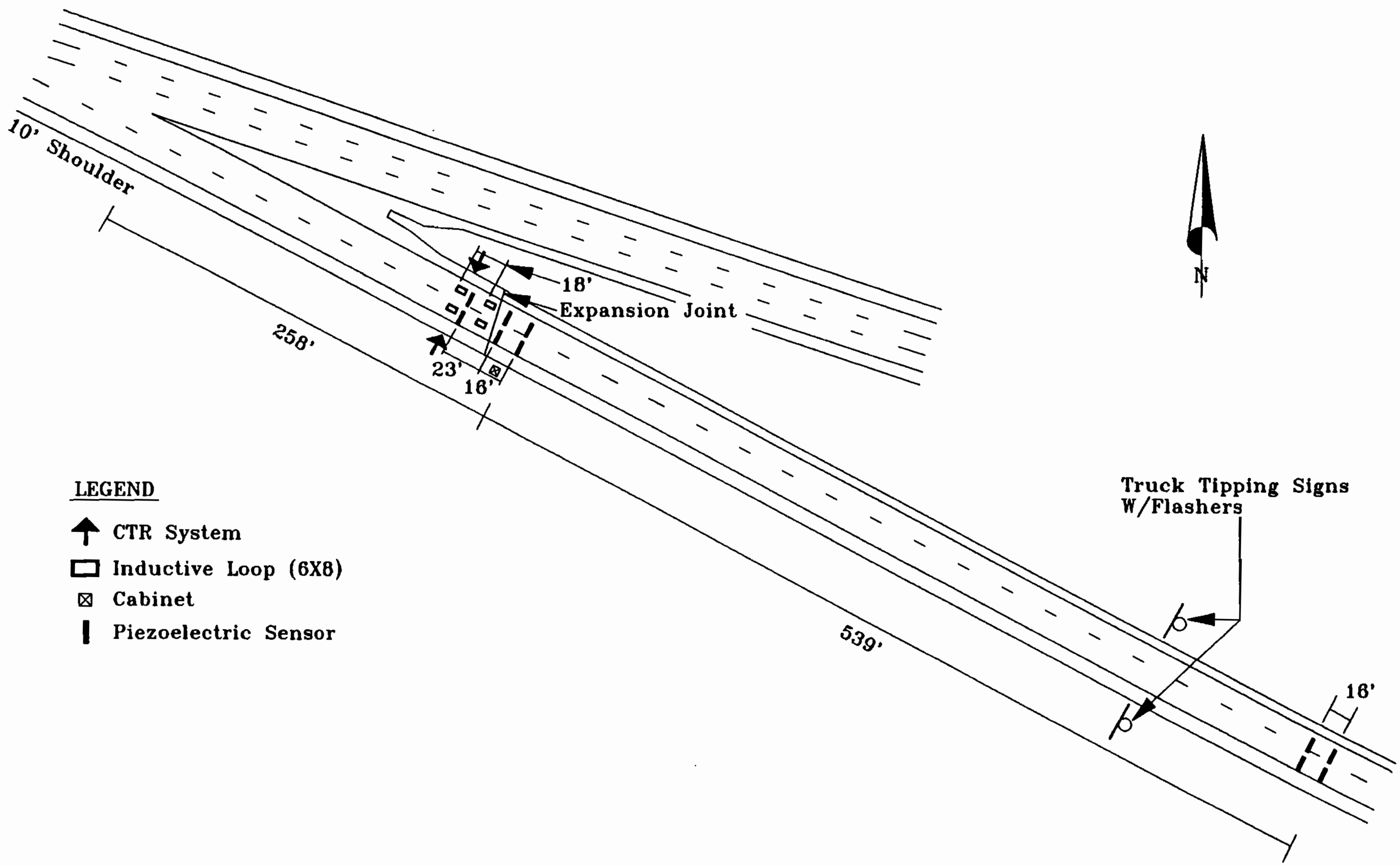


Figure 1-3. Sensor Layout at Locations A and B

Table 1-1. Off-Peak Traffic Speed Summary Before Treatment

	Func. Class	No.	Speeds (mph)			
			Maximum	Minimum	Mean	Std.Dev.
Loc. A	1-2	1197	76	25	56.2	6.0
(6/25/92)	3-5	31	69	20	45.3	12.0
	6-13	116	65	20	50.7	9.5
Loc. B	1-2	2662	77	24	52.6	5.3
(6/16/92)	3.5	62	61	20	43.2	10.4
	6-13	277	65	25	48.6	6.4
Loc. C	1-2	2340	84	21	48.3	5.0
(6/16/92)	3-5	40	56	22	41.5	7.3
	6-13	251	54	21	42.7	5.4

Metric Conversion: 1 mph = 1.61 km/h

The average daily traffic volume as counted by the IRD classifiers for a seven-day period at Location A beginning June 17, 1992 was 11,924 vpd. For the Wednesday of that week (typical of weekdays), the total traffic volume counted was 12,251 vehicles (10.2 percent trucks in functional class 4 through class 13). The appendix includes a list of vehicles by functional class as defined by the Federal Highway Administration's Traffic Monitoring Guide (1). According to the IRD classification count, 69 percent of the class 4 through 13 trucks were in the right lane at Location A. The IRD count for the Saturday of this week was 11,408 vehicles (6.2 percent trucks in functional class 4 through class 13).

Vehicular loss of control and/or truck incidents were evident from damage to the right-hand barrier and numerous tire marks and metal gouges along the outside of the first curve, extending almost to the second curve. Shoulder tiles, which are virtually intact along the approach to the first curve, have been substantially removed along the outside of the first curve. An accident investigation through the State Department of Public Safety (DPS) revealed several accidents involving large trucks on the subject connector. Over the six-year period from 1985 through 1990, DPS records showed a total of twenty-two accidents involving large trucks at this interchange. There were as many as eight accidents involving large trucks in one year. Unfortunately, details on the accident reports were insufficient to determine how many occurred on the subject connector.

CHAPTER 2. TRAFFIC MONITORING SYSTEMS

INTRODUCTION

Beginning on August 5, 1990, TTI installed several components of a traffic monitoring system for the I-610 eastbound to US-59 northbound connector. Included were: an aluminum cabinet mounted on a 30-inch (0.76 m) aluminum pedestal, 1,200 feet (366 m) of 2 1/2 inch (63.5 mm) conduit welded to the right-hand bridge rail, AC power and phone line to the cabinet, and various sensors placed beside, on top of, or in the pavement. The purpose of the conduit was for communications and AC power which could be run from the cabinet as needed. The initial pavement sensors included several piezoelectric and loop configurations generally located near the beginning of the ramp and both upstream and downstream of the first curve of the ramp.

Upon further evaluation in 1992, the monitoring locations of pavement sensors downstream of the cabinet were modified; sensor locations near the cabinet remained essentially unchanged. Positioning of sensors was designed to capture speeds at the beginning of the ramp and as vehicles entered the two horizontal curves. The first location was adjacent to the cabinet near the ramp gore, the second was at the point of curvature (PC) of the first curve, and the third was at the PC of the second curve. Figure 1-2 shows these locations. Each monitoring station included the sensors mounted on or in the pavement and a microprocessor-based system for recording information about the vehicles.

TTI evaluated several alternatives for a system which could monitor traffic, provide power to monitoring stations, and provide communications from the monitoring stations to the cabinet. This process resulted in the selection of three stand-alone vehicle classifiers using their own power sources (internal battery) while coordinating their internal time clocks to avoid the necessity of communications. This time coordination (setting each classifier clock to correspond to a common source) provided the capability of tracking target vehicles, given the vehicle's speed at each monitoring location and the distance to the next monitoring location.

The Center for Transportation Research (CTR) of the University of Texas at Austin installed another system of sensors on this connector roadway in 1992 using infrared technology. The first installation of these roadside sensors was located just upstream of the cabinet; a second installation was added later near the PC of the first curve. More information on these systems is provided below.

TTI used a number of different types of surface sensors on the I-610/US-59 connector to monitor traffic. The tests were intended to determine the reliability and durability of each sensor type under high speed, high traffic volume conditions, with a significant number of trucks. Temporary sensors were monitored until they failed or were no longer functional for the purposes intended. In all cases but one, signals generated by the sensors were used to classify and/or to count traffic and to monitor speeds. The exception was the conductive plastic inductive loops, which were not used to classify or count vehicles because they did not generate an acceptable signal for this purpose.

In most cases, sensors generated signals that were interpreted and stored by three IRD Series 500 vehicle classifiers. These classifiers could store information on vehicle speed, date, time, number of axles, wheelbase, and classification in either a "binned" or "raw" mode. Only in the raw data mode could vehicle-specific information be stored. The IRD system was typically used in the raw data mode so that for each of the three locations on the ramp any vehicle (particularly trucks) could be "tracked" by coordinating the time clocks on all three classifiers and by knowing or calculating the expected travel time between stations. Identification of the same vehicle at each of the three sites was relatively straightforward either manually or by a computer program which matched a vehicle "footprint" at Location A with one which was reasonably close to the same physical dimensions at B and C and which passed the other two locations within a reasonable time window.

The IRD system had the advantage over other alternatives of not requiring communications between sites and not requiring AC power from a local source. Time clock coordination removed the need for communications, and the IRD classifiers used an internal battery for its power source. AC power was available at the cabinet if needed to recharge internal classifier batteries.

SURFACE SENSORS

Temporary Plastic Loops

In August 1990, TTI personnel installed a system of conductive plastic inductive loops on the ramp. Elf-Atochem North America (Pennwalt at that time) manufactured the loops solely for use on this ramp. The loops were made of 1/8 inch (3.18 mm) diameter conductive plastic cable, and were intended to serve as very rugged, durable inductive loops. The installation process on the roadway was similar to that typically used for copper wire inductive loops; three turns of the experimental cable were placed at a depth of approximately 1 1/2 inches (38 mm) in the 6-foot (1.83 m) by 6-foot (1.83 m) saw cuts.

The conductive plastic inductive loops were designed to take advantage of the high tensile strength of a plastic polymer known as polyvinylidene fluoride (PVDF). The sensors consist of a layer of conductive (silver) ink applied to a cable fabricated from PVDF. The PVDF and conductive ink have been shown to be very durable, tough, and flexible even in extremely harsh environments.

Laboratory testing of the conductive plastic prototype under repeated loading indicated that it had an excellent chance of providing a highly reliable vehicle presence traffic sensor. However, testing of the inductance and other properties prior to field installation demonstrated that the signal would, in all likelihood, require modification for use with a commercially available vehicle classifier. Field testing of the plastic loops just after installation verified this suspicion when attempts at classification using a PAT classifier were unsuccessful. Technicians were unable to get the loops to "tune." When tested on July 31, 1992 after approximately two years of being in the pavement, all four loops were discontinuous (had breaks) and had very low capacitance readings. No attempts were made to repair or replace these sensors due to their poor signal qualities.

Temporary Piezoelectric Sensors

On May 31, 1992, TTI installed twelve "TP" series piezoelectric film sensors manufactured by AMP Incorporated of Valley Forge, Pennsylvania (previously Elf Atochem North America) on the ramp, which were used to generate signals for the three IRD Series 500 classifiers. The general locations of these sensors are shown in Figure 1-2. In the original installation on May 31, 1992, the distance between these sensors at each monitoring station was 16 feet (4.88 m). Vehicle classification required two of these axle sensors in each lane, so a total of four sensors were used at each of the three locations on the ramp. Some of these sensors were replaced by piezoelectric cable sensors as they failed. Both cable and film sensors use *KYNAR* film as a transducer material. In this application, they transform a mechanical force to an electrical response. *KYNAR* Piezo Film is based on PVDF, which exhibits high piezo and pyroelectric activity.

To keep these TP sensors in position, TTI initially used a primer painted directly on the pavement surface, followed by one layer of a scale tape material called Polygard across the entire lane width. After a few minutes of curing time (depends on ambient temperature), TTI then placed a new piezo sensor directly on top of and in the center of the Polygard, being careful to maintain its position relative to the other sensor in the same lane. At least one layer (preferably two layers) of Polygard covered the sensor in an overlapping fashion to maintain its position relative to the other sensor and to protect it from traffic. Six-inch (152 mm) widths of Polygard were typically used, although 4-inch (102 mm) widths were also occasionally used. Figures 2-1 through 2-4 show the initial process of placing these sensors on the pavement. Efforts used to protect sensors and coaxial cables from damage included placement of raised pavement markers adjacent to the terminal block of each sensor and placing coaxial cables behind (downstream) shoulder tiles.

The placement of these particular sensors on the bridge deck was in itself problematic for a number of reasons. The first problem was that placing these sensors on the pavement or making repairs to them was intrusive or disruptive to normal traffic. Sometimes the usable ramp width was reduced from two lanes to one, while other repair or installation scenarios required complete ramp closure. The initial installation and some of the subsequent repairs required complete closure of the ramp for several hours. It was the policy of Texas Department of Transportation (TxDOT) not to allow complete closure of the ramp except on Sunday mornings, and even then, they required that it would be reopened as soon as possible, but no later than 1:00 pm. This required TTI to begin at daylight and work as quickly as possible to complete work during the allowable time period. If all repairs were not completed in that time period, another closure would be required on another Sunday morning. Even during weekdays when one ramp lane remained open, TxDOT allowed work only between 9:00 am and 3:00 pm. In any case, the cost of traffic control was significant as were delays to motorists, especially when traffic was detoured to the next interchange to the east (Lockwood Street).

The second problem was a result of not being able to effectively protect these temporary sensors on a bridge deck. For example, a motorist with a flat tire on the ramp might drive the entire length of the ramp on the rim to reach a safe stopping location, possibly damaging sensors and/or coaxial cables throughout. Other damage occurred by

Figure 2-1. Applying Polygard and Primer for Piezo Sensors

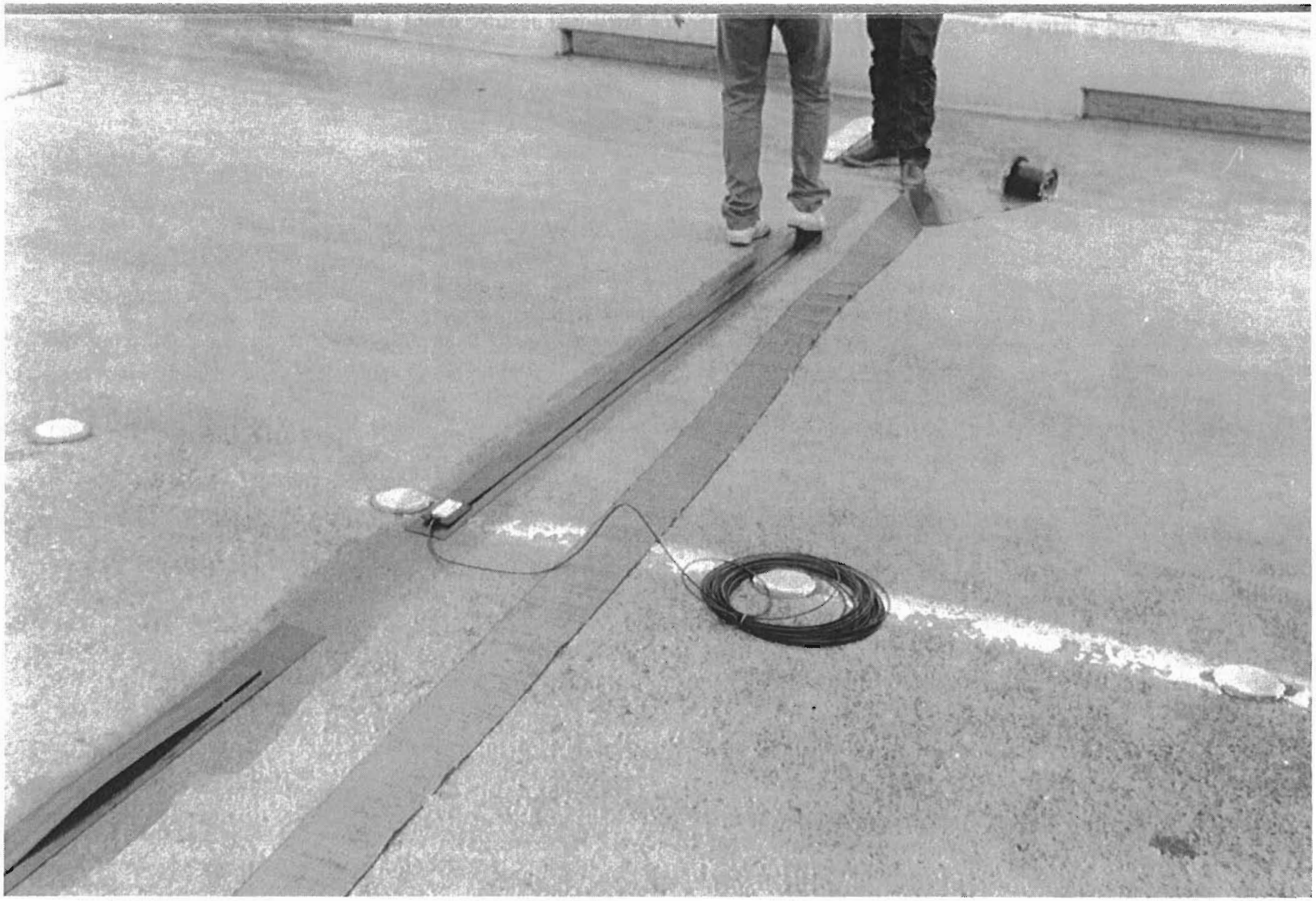


Figure 2-2. Lane 2 Piezo Sensor Prior to Covering with Polygard

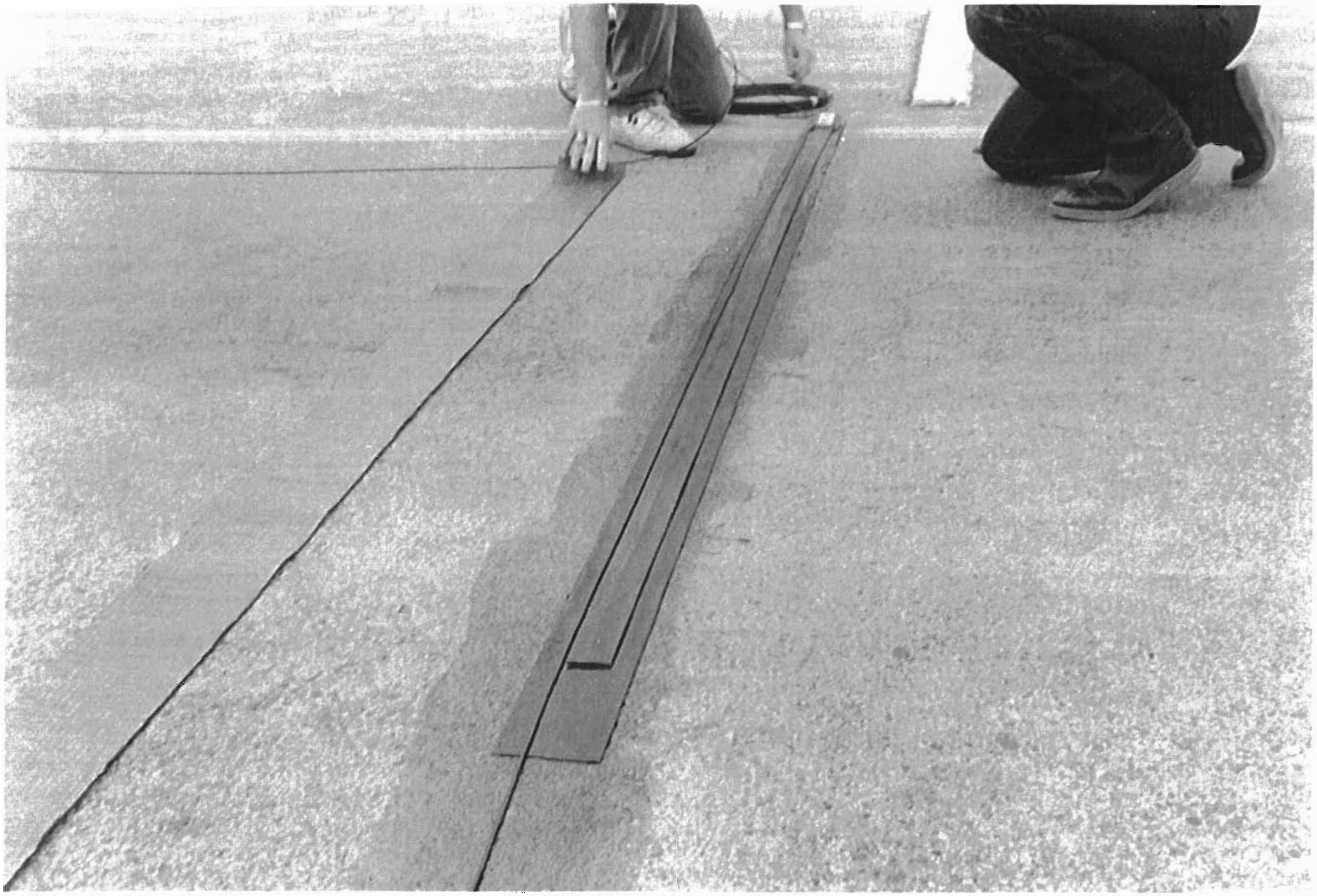


Figure 2-3. Lane 1 Piezo Sensor Showing Placement of Coaxial Cable from Lane 2 Sensor

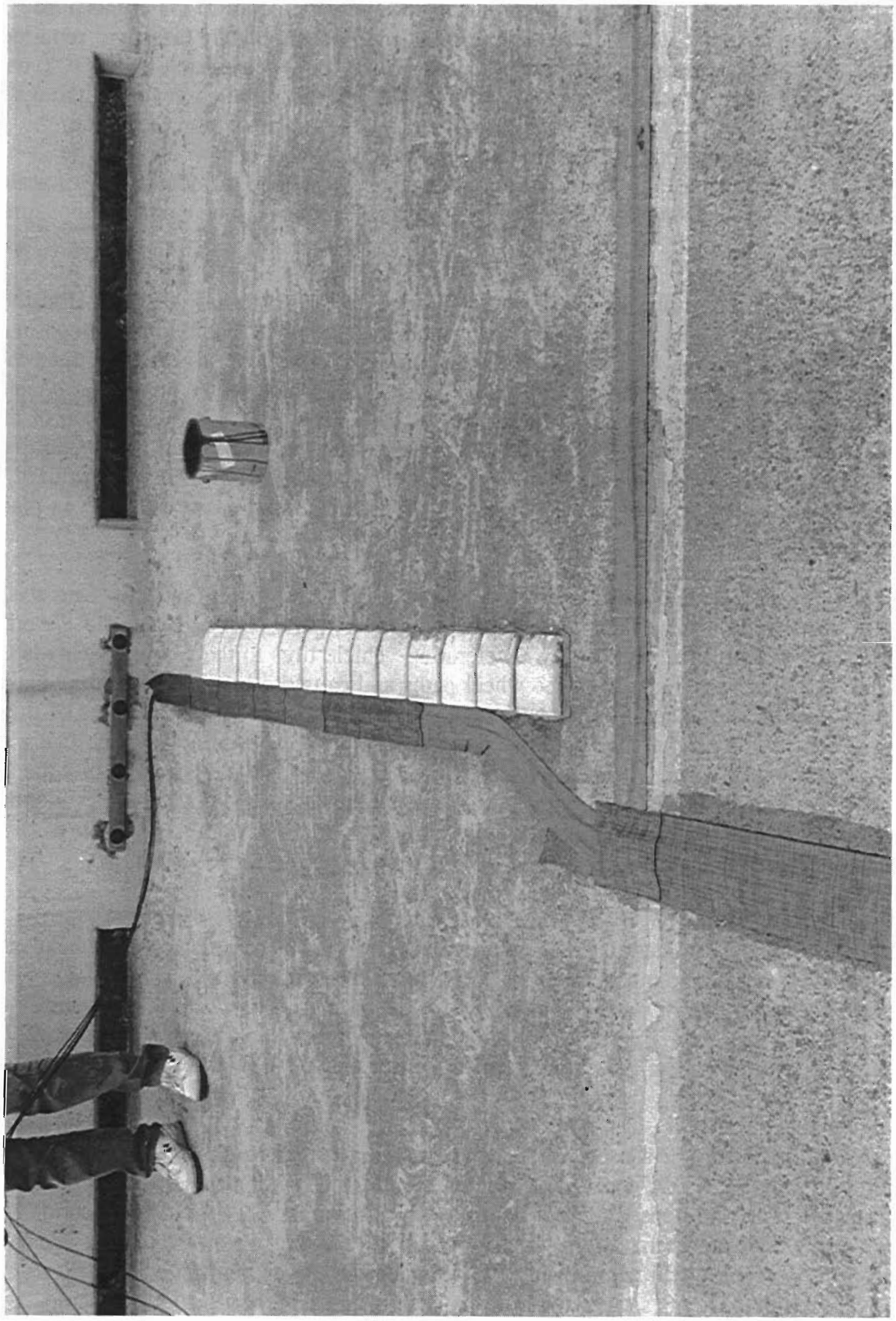


Figure 2-4. Shoulder Treatment of Coaxial Cables

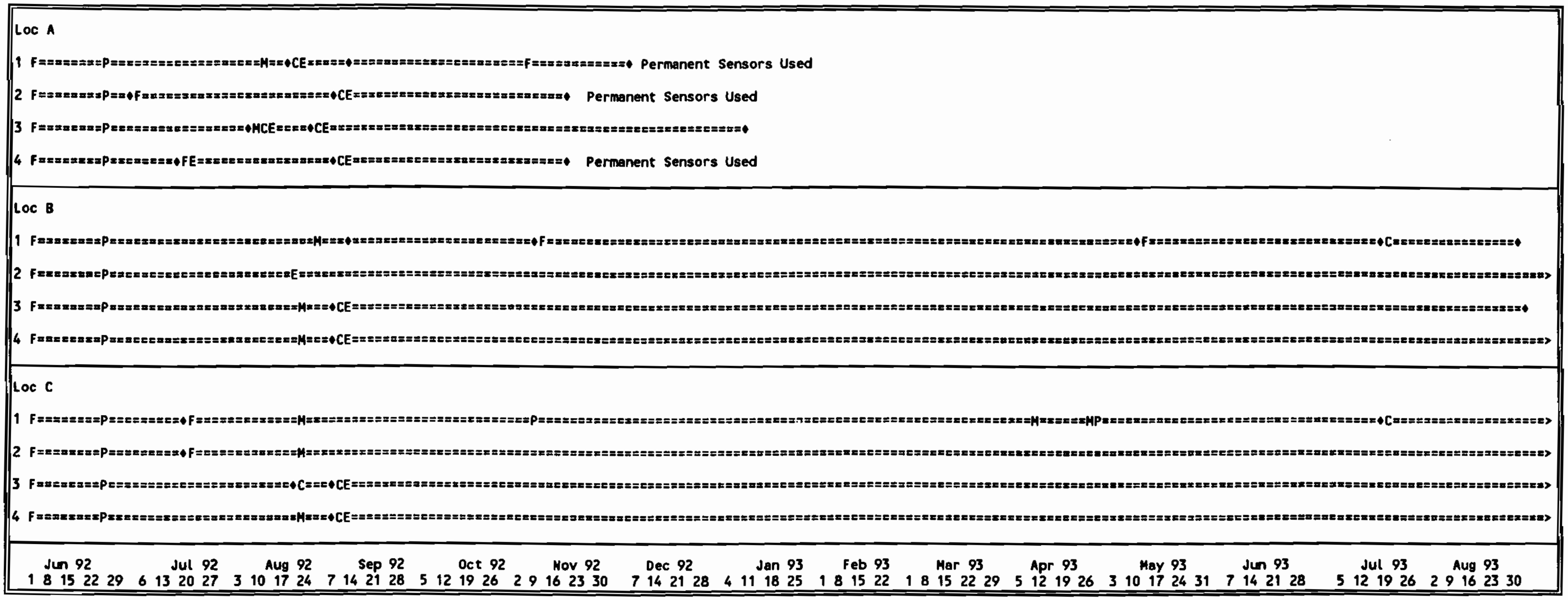
metallic objects (e.g., mufflers or tail pipes) being dragged across the sensors or coaxial cables. Even a minor cut of the insulation on the coaxial cable could result in moisture absorption, grounding the sensor. Protection, in order to be completely effective, required saw cuts to depress the sensors to a flush position. This was not acceptable to TxDOT on a structure, and even off structures would add significantly to the installation cost (although it would probably save money overall). Therefore, an alternative protection technique consisting of a wedge of epoxy behind the sensors to both protect and secure them to maintain their position was attempted during this study. Then, one or more layers of scale tape was added over the top to hold the sensor in place and reduce the amount of moisture penetration.

The epoxy used to protect the sensors was a product of BradCo Plastics of Houston. This particular product was selected because it retained some of its flexibility as it continued the curing process. Its removal (if necessary) was thought to be less of a problem than the more brittle epoxies available for roadway use. Even though it remained somewhat pliable, the user must still be extremely careful not to allow the epoxy to extend over the top of the sensor. Otherwise, the signal generated by the sensor would be weakened to the point that it could become ineffective. The epoxy was not used on all sensors, but where it was used, the epoxy successfully kept sensors in position. In some locations, the epoxy has been in place for over a year.

The use of these temporary sensors produced at least two failure modes. One was simply from repeated loadings from heavy traffic volumes, particularly trucks, and the other was due to the lateral forces applied by decelerating vehicle tires to the sensors. This latter effect shoved the sensors forward in the wheel paths and caused a breakdown in the bond between the adhesive material and the pavement. After an extended period of time of this shoving action in hot weather, the adhesive bond was so weak or even nonexistent that a passing vehicle would cause visible movement in the sensor. It should be noted that the slippage of the sensors in the wheelpaths was not apparent during the cooler winter months of January, February, and part of March, as depicted by Figure 2-5. This figure is a summary of repairs and/or failures of both film and cable piezoelectric sensors.

Attempts to straighten these deformed sensors were not always successful. Stress created by the removal process sometimes caused failure, and at other times the sensor or its coaxial cable were inadvertently cut during the repair. The coaxial cable was always protected underneath one or more layers of scale tape and was difficult to locate before cutting away old material. Figure 2-6 illustrates sensor deformation in lane 2; Figure 2-7 illustrates a later view of the lane 2 replacement sensor and the lane 1 sensor beginning to shift.

A total of thirty-one sensors were required during the 65 weeks of the test period beginning on May 31, 1992, and ending August 30, 1993. Temporary sensors were used for the entire period at Locations B and C, but only through January 8, 1993, for Location A. Because of the high failure rate of TP sensors at Location A and after discovering that the permanent sensors were still operational, TTI resumed the use of the permanent sensors. Table 2-1 is a summary of sensor durability at each of the three stations on the ramp. Location A required twelve sensors over a time period of 32 weeks; Locations B and C



Legend of Symbols:

F = Film Sensor Installed
C = Cable Sensor Installed
M = Maintenance to include Straightening Sensor
P = Polygard added
E = Epoxy used
♦ = Failure
1,2,3,4 = Sensor Number

Sensor Number Designation

Lane 2 →	3	4
Lane 1 →	1	2

Figure 2-5. TP Sensor Replacement and Repair History

Figure 2-6. Deformed Piezo Sensors at Location C

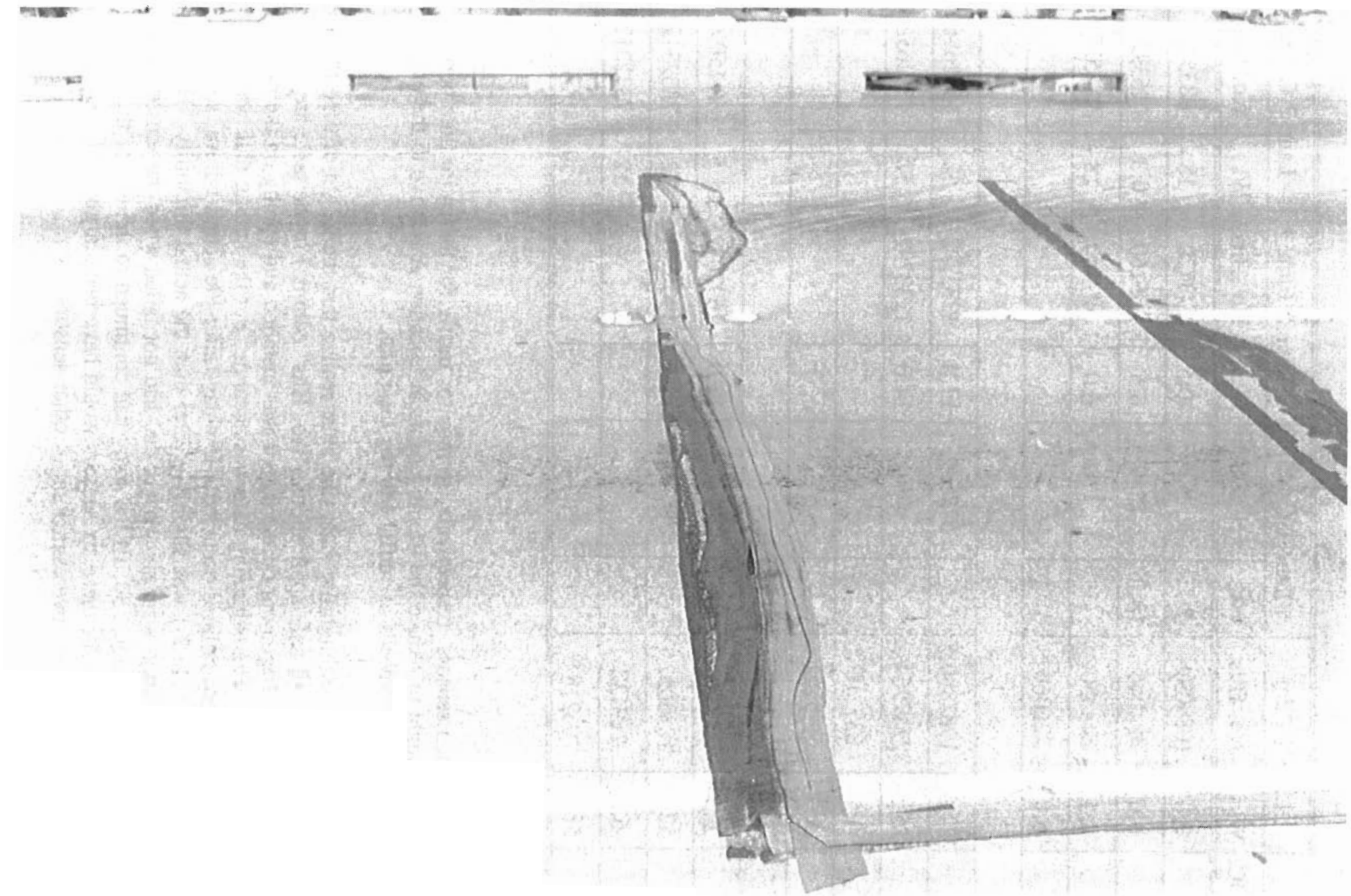


Figure 2-7. Location C Following Replacement of Lane 2 Piezo Sensor

Table 2-1. TP Sensor Durability Summary

	Lane 1 Film		Lane 1 Cable		Lane 2 Film		Lane 2 Cable	
LOC.	Wks.	No. Hits	Wks.	No.Hits	Wks.	No. Hits	Wks.	No. Hits
A	9.0	1089099	2.5	302528	10.5	573720	18	983520
	4.0	484044	18.0	2178198	6.5	355160	0.3	16392
	4.5	544550			6.0	327840	18	983520
	6.0	726066						
B	22.5	1982880	6.5	572832	14.0	1233792	52	4582656
	25.5	2247264			14.0	1233792	52	4582656
	9.5	837216						
	65.5	5772384						
C	6.5	229132	6.5	229132	12.0	1692072	1.5	211509
	52.0	1833052			13.5	1903581	52	7332312
	6.5	229132					52	7332312
	58.5	2062184						

required nine and ten sensors, respectively, to monitor traffic for the entire time period. One factor which is thought to reduce the life of sensors at Location A relative to the other two locations was the higher speeds as traffic entered the ramp.

In evaluating these durability data, one must realize that the length of time ("Wks." column) and the number of axle applications ("No. Hits" column) in the table are based on each sensor's useful life beginning on the date it was installed and ending on the date its failure was discovered. The beginning date was accurate, but the ending date was not. In actuality, the discovery of failures occurred a few days after the actual failure, so the recorded durability in Table 2-1 was slightly greater than the actual durability. However, offsetting this overestimation were six sensors that had not failed when the sensor durability evaluation concluded on August 30. If the study had continued to the end of their actual useful life, the table values for these six sensors would have been larger. This omission compensates for (some of) the overestimation of other sensors.

Another factor which undoubtedly affected the life of these temporary sensors was the amount of traffic volume, especially trucks. Even though the total traffic volume is constant throughout the length of the ramp, lane 1 volume is different from lane 2, and the split by lane is different at the three locations. At Location A, 70 percent of the total traffic is in lane 1, at Location B, this is reduced to 50 percent, and at Location C, it is further reduced to 20 percent. Using these percentages and the number of weeks each sensor endured, the number of axle load applications are determined as shown in Table 2-1.

Based on limited laboratory testing by TTI and the manufacturer's experience, the life of these TP sensors is thought to be approximately one million axle applications. This is apparently a gross approximation, given that it does not distinguish between wheel loads of trucks versus smaller vehicles. Obviously, truck wheel loads are heavier than those for smaller vehicles, and reductions in sensor life should be greater as the proportions of trucks increase. Table 2-1 shows only total (mixed vehicle) applications without distinction between trucks and smaller vehicles. One of the concerns caused by these tabulated data is the extreme variation in the useful life of these sensors. This translates into the unpredictability of how long a sensor, once installed, will remain functional.

Yet another important consideration in evaluating the durability of these sensors is the weather. During the extended hot summer weather in Houston, there were more problems due to sensors shifting out of position than during cooler weather where no epoxy was used. Therefore, failure rates were typically higher unless epoxy was used or unless the sensors were straightened often and recovered with new Polygard. The difference in sensor durability between summer and winter temperatures is evident in Figure 2-5. During the months of November through March, maintenance and replacement activities were practically nonexistent.

Permanent Sensors

TTI installed one permanent set of sensors on the ramp near the cabinet just downstream of the ramp gore. These sensors included two 6-foot by 8-foot (1.83m by 2.44m) copper wire inductive loops with one permanent piezoelectric sensor between the two loops. To install these sensors, TTI used a pavement saw to cut slots in the pavement to the proper dimensions for both the piezoelectric sensors and the inductive loops. Then, to continue installation of the piezo sensors, they used flexible aluminum tabs to support the sensor over the slot in the correct position. The next step required backfilling the piezo sensor slot with an epoxy grout, ensuring that the sensor remained in the proper position throughout the pouring and curing process. The piezo-film sensors were placed so that the top surface was 1/8 inch (3.17 mm) below the surface of the roadway. When the epoxy had cured sufficiently, three layers of scale tape (e.g., Polygard) were placed over the sensor to ensure that wheel loads were transferred to the sensors underneath. A sealant material was used to backfill the inductive loop slots once the three turns of copper wire were in place.

Each permanent piezoelectric sensor consists of a 1-inch (25.4 mm) square cross-section U-shaped aluminum channel that contains the piezo-film strip surrounded by an elastomer. The sensor is 75 inches (1.91 m) in length and comes with 100 feet (30.5 m) of coaxial cable. TTI positioned one piezo sensor in each lane in the right-hand wheel path at a

90-degree angle to the direction of traffic. The two inductive loops were placed 18 feet (5.49 m) apart and the piezo sensor was placed between them. The primary purpose of the inductive loops in this scenario was to allow speed monitoring; the secondary purpose was to detect presence.

The permanent sensors, which were installed during the summer of 1990, were the only pavement sensors tested at this site which provided continuous, reliable signals throughout the duration of the study. The only maintenance required during the 65-week study was adding Polygard to the top of the piezo sensors on two occasions. This experience and others have demonstrated, however, that inductive loops are not as accurate as piezo sensors for monitoring speeds. Given the propensity of motorists on this particular ramp to change lanes, a better system of pavement sensors would have utilized two permanent piezo sensors spaced at 16 feet (4.88 m) with one permanent inductive loop located between them.

ROADSIDE SENSORS

Photoelectric sensors have been used since the 1950s when incandescent lamps were used with cadmium sulfide photocells in systems commonly called electric eyes. When sufficient light hits the surface of the photocell, it acts as a transducer and conducts current to an output device. If the light is blocked, the current stops for the amount of time of the light blockage. In the 1970s, light-emitting diodes (LEDs) became commercially available and were much more desirable than incandescent lamps for this application because of their longer life span and their durability under harsh conditions. Probably their biggest advantage, however, is their ability to be modulated thousands of times per second. LEDs operate in several visible-light wavelengths as well as infrared, but infrared LEDs are often preferred because they emit more light intensity than visible-light LEDs and because most photodetectors are more sensitive in the infrared range (2). One disadvantage of infrared LEDs when compared to visible light LEDs is greater difficulty of alignment.

Photoelectric sensors are typically used in one of three modes or configurations. The one which is appropriate when measuring vehicle height, as on the I-610/US-59 connector, is called direct, opposed, or through-beam. The LED source and detector are in separate, opposing locations, and the object to be sensed passes between them and breaks the light beam. The other two variations utilize the LED source and receiver in a side-by-side configuration with the beam reflected to the receiver either by a target retroreflector on the opposite side of the lane (broken by vehicle passage) or by a passing vehicle which reflects the beam. The direct sensing mode is advantageous due to its long range, although this is not a factor on most freeway connectors. A disadvantage of this mode when used on a two-lane connector is the possibility of measuring two side-by-side vehicles and "seeing" them as one. For applications where traffic volumes are low to moderate, this is not perceived as a significant problem.

The Center for Transportation Research (CTR) of the University of Texas at Austin installed and tested infrared (IR) sensors at two locations on the I-610/US-59 ramp to monitor trucks. CTR personnel began testing IR monitoring systems for counting and classifying vehicles in 1988 and installed a system in Houston to detect wrong-way movements on High Occupancy Vehicle lanes in 1989. In 1990, a test was performed in

Jarrell, Texas to evaluate long-term performance and durability and to compare output with loop detectors and piezoelectric cable sensors. For the I-610/US-59 ramp, the system was set to monitor vehicles which are over 16 feet (4.88 m) in length and over 7 feet 1 inch (2.16 m) in height. These dimensions reflect those of large trucks which are more likely to have high centers of gravity and thus be subject to rollover. A shorter height is undesirable because sensor beams would be broken by four-tire vans with equipment affixed to the roof.

Each location initially utilized a two-beam infrared sensor array with the IR source on the right-hand side of the ramp and the receiver on the left-hand side. The sensors were placed 2 feet (0.61 m) apart, oriented at a 90-degree angle to the direction of traffic. A metal pedestal, fastened to the barrier rail by clamps, supported the array. Source and receiver were located approximately 38 feet (11.59 m) apart. The initial installation of IR sensors on the ramp was near the cabinet to facilitate connection to AC power and for ease of comparisons to other systems. This system required AC power on a continuous basis; however, a battery was provided to sustain data collection during short power outages. This initial installation used an array of two infrared sensors spaced 2 feet (0.61m) apart (as measured in the horizontal plane) on either side of the roadway. A later modification to each pedestal reduced the height of these two sensors to 40 inches (1.02 m) with a third sensor added at the original height (7 feet - 1 inch [2.16 m]) of the two sensor array.

Among the advantages of the IR sensors as used on the I-610/US-59 ramp is the fact that they are less intrusive to the traffic stream than sensors on the pavement. There is little interference with traffic on the roadway and no lane closures are required if power cable can be run underneath the roadway. For maintenance activities, the shoulder was sufficiently wide on the I-610/US-59 ramp to park vehicles without obstructing traffic. Their relatively low cost is another advantage. Also, when compared to the pavement sensors used in this study, they were more effective in monitoring vehicles that change lanes near sensors. Advantages related to data collection are discussed in another section.

Problems experienced during the use of the IR sensors were not always the fault of the CTR hardware and/or software. There were a few power failures during the 65-week study period which resulted in sporadic or no data collection during the time period. A gel-cell battery was available in the cabinet for auxiliary power during short power outages. Also, a few outages might have occurred due to power surges, even though a surge protector was provided in the cabinet. An early problem occurred with (apparently) mice getting into the cabinet and causing damage to electronic components. This was solved by sealing problem areas against intrusion. On at least one occasion, a vehicle struck the IR target on the left-hand shoulder near the cabinet, knocking it out of alignment. This was easily corrected by rotating the support back to the original position and tightening the clamps which maintain its alignment.

Other problems experienced with the IR system were inherent to the system. During normal operations, alignment of the beams was very stable at the cabinet location, but the second (slave) system located near the first horizontal curve was more difficult to align due to bridge vibration and required more attention periodically for realignment. With the two-beam system first used at the cabinet, a problem resulted from the IR beams striking the windshield of large trucks. Apparently, on some trucks, one beam would be broken by the windshield surface and the other beam would not. On May 3, 1993, CTR personnel corrected this problem by adding a third IR sensor on this pedestal. The new configuration lowered the original two-beam array to a height of 40-inches (1.02 m) above the pavement and added the third beam at the original 7 feet - 1 inch (2.16 m) height, all three mounted on the same pedestal. This third beam would serve as the length measurement while the lower two-beam system would still detect speeds.

Another problem with the original two-beam system consisted of having detectors set at the same height as the top of a vehicle. Apparently, one IR beam was broken by the vehicle and the other was not. The result was erratic speed data. An example is a four-tire van with a ladder on its roof. CTR adjusted the height and modified their software to reduce this problem. Finally, the CTR system can miss a few relatively high center-of-gravity vehicles because of their atypical load dimensions. An example is a flatbed loaded with two large rolls of steel, one in front and one in back.

CHAPTER 3. RESULTS

SPEED COMPARISONS USING RADAR

Sensors tested in this study are components in systems which are intended to monitor speeds of trucks under a selected set of scenarios. The accuracy of speed measurement was very important in determining the effectiveness of traffic warning devices displayed to truck drivers. Conclusions regarding accuracy were based on comparison of each individual system with a detuned radar gun and with each other.

Temporary Piezoelectric Sensors

TTI evaluated speeds generated by the IRD system employing the temporary piezo (TP) sensors by using a detuned radar gun. This short study used either large vehicles or vehicles which would otherwise not be confused in the speed comparison process, such as an isolated vehicle without other background vehicles nearby. Tables 3-1, 3-2, and 3-3 provide results of studies conducted on August 11, 1992 at Locations A, B, and C.

Conducting this comparison of speeds from two different sources, while informative, must be interpreted carefully. For purposes of this study, the accuracy of the radar unit *per se* is sufficient, even though detuning is known to require a very modest correction. A more significant factor is being able to match the same vehicle monitored by the radar system with the one monitored by the IRD system. The human observer must possess certain skills to correctly interpret output from the radar system. Once the radar unit locks onto a vehicle, the observer must follow, or track, the vehicle and know its location with respect to the pavement and roadside sensors. An accurate comparison of speeds requires the observer to note the radar speed reading in a very precise manner. Because most vehicles are decelerating on this ramp, the accuracy of the comparison depends upon reading the radar output at exactly the moment the IRD or roadside system records the vehicle. This occurs a few milliseconds after the last axle of the vehicle crosses the downstream sensor. From a practical standpoint, the observer should record the radar speed when the last axle crosses the downstream sensor. For the roadside sensors, time is recorded when the rear end of the vehicle passes the sensor beams.

Permanent Piezoelectric Sensors

TTI also conducted speed comparisons on the IRD system using the permanent piezoelectric sensors. As noted earlier in this report, the inductive loops are not considered as accurate for speed studies as axle (piezo) sensors. After comparing the output of the radar gun with IRD output at Location A, it was obvious that lane 2 speeds generated by the IRD using inductive loops were too high. Applying an appropriate correction factor resulted in changing the actual 18-foot (5.49 m) spacing to a 15-foot (4.57 m) nominal spacing to correct speed readings from the IRD system. For lane 1, this correction was not necessary. There was no obvious reason why lane 2 was different from lane 1, but this correction caused the lane 2 data to agree much more closely with radar output.

Table 3-1. Speed Comparisons of Temporary Piezo Sensors and Radar - Location A

Vehicle No.	Vehicle Class	Radar Speed (mph)	IRD Speed (mph)	Comment
1	SU-2	42	42	
2	3-S2	54	55	
3	SU-3	48	49	
4	3-S3	50	51	Clear view
5	PC	47	47	
6	PC	53	57	
7	3-S2	45	48	
8	P/U	59	59	Isolated
9	P/U	59	61	
10	P/U	58	58	
11	PC	54	54	
12	PC	45	46	
13	P/U	57	56	
14	P/U	61	--	
15	PC	51	53	
16	PC	55	54	
17	P/U	65	63	
18	3-S2	52	53	
Mean		53.1	53.3	
Std. Dev.		6.01	5.45	

-- Not able to positively identify the correct vehicle from IRD output.

Metric Conversion: 1 mph = 1.61 km/h

Table 3-2. Speed Comparisons of Temporary Piezo Sensors and Radar - Location B

Vehicle No.	Vehicle Class	Radar Speed (mph)	IRD Speed (mph)	Comment
1	SU-3	43	43	Bobtail
2	SU-3	42	41	Clear view
3	3-S2	48	--	
4	SU-3	42	40	
5	3-S2	46	--	
6	3-S2	40	--	
7	SU-2	40	38	Lane 2
8	3-S2	46	44	Clear view
9	PC	50	46	
10	PC	49	48	Isolated
Mean		44.6	42.9	
Std. Dev.		3.50	3.23	

-- Not able to positively identify correct vehicle from IRD output.

Metric Conversion: 1 mph = 1.61 km/h

Table 3-3. Speed Comparisons of Temporary Piezo Sensors and Radar - Location C

Vehicle No.	Vehicle Class	Radar Speed (mph)	IRD Speed (mph)	Comment
1	3-S2	43	42	
2	PU	39	38	
3	PU	49	48	
4	PU	42	42	
5	PU	45	44	
6	MC	61	60	Motorcycle policeman
7	PU	38	38	
8	3-S2	38	37	
9	3-S2	37	40	
10	SU-2	45	46	
11	3-S2	44	44	
12	3-S2	42	42	
13	PU	44	44	Isolated
14	SU-2	44	44	
15	3-S2	32	32	
16	PC	55	55	Isolated
17	3-S2	35	34	Isolated
18	PU	45	44	Isolated
19	2-S1	40	40	
Mean		43.1	42.8	
Std. Dev.		6.56	6.41	

Metric Conversion: 1 mph = 1.61 km/h

Tables 3-4, 3-5, and 3-6 provide comparisons of data collected by the IRD system and radar on September 15, 1992. Table 3-4 data utilized permanent sensors (two inductive loops and one permanent piezo sensor) at Location A, whereas Tables 3-5 and 3-6 data

Table 3-4. Speed Comparisons Between Permanent Sensors and Radar at Location A

Veh.No.	Radar	IRD	Abs. Diff.
1	56	54	2
2	61	61	0
3	59	58	1
4	53	53	0
5	50	50	0
6	56	57	1
7	43	42	1
8	59	56	3
9	65	70	5
10	50	52	2
11	53	53	0
12	54	53	1
13	69	70	1
14	60	57	3
15	57	56	1
16	61	61	0
17	45	45	0
18	48	48	0
19	60	61	1
20	45	46	1
21	56	57	1
22	58	56	2
23	50	49	1
24	53	46	7
25	45	47	2
26	62	63	1
27	51	52	1

Table 3-4. Speed Comparisons Between Permanent Sensors and Radar at Location A (continued)

Veh.No.	Radar	IRD	Abs. Diff.
28	30	33	3
29	48	50	2
30	61	63	2
31	62	63	1
32	43	43	0
33	52	53	1
34	54	54	0
35	71	72	1
36	67	69	2
37	43	46	3
38	56	57	1
39	56	57	1
40	56	55	1
41	60	59	1
42	58	58	0
43	61	59	2
44	54	54	0
45	50	50	0
Mean	54.7	54.8	1.31
Std.Dev.	7.69	7.76	1.36

Metric Conversion: 1 mph = 1.61 km/h

Table 3-5. Speed Comparisons Between TP Sensors and Radar at Location B

Veh. No.	Radar	IRD	Abs.Diff.
1	40	41	1
2	44	46	2
3	35	37	2
4	50	52	2
5	59	60	1
6	43	44	1
7	48	48	0
8	38	40	2
9	48	48	0
10	50	50	0
11	42	44	2
12	49	50	1
13	41	42	1
14	58	60	2
15	46	48	2
16	55	55	0
17	48	49	1
18	49	50	1
19	49	50	1
20	51	52	1
21	45	48	3
22	46	48	2
23	49	53	4
24	48	51	3
25	46	47	1

Table 3-5. Speed Comparisons Between TP Sensors and Radar at Location B (continued)

Veh. No.	Radar	IRD	Abs.Diff.
26	40	43	3
27	47	48	1
28	46	46	0
29	39	42	3
30	53	54	1
31	42	42	0
32	56	57	1
33	51	52	1
34	44	45	1
35	50	51	1
36	46	48	2
Mean	47.0	48.4	1.39
Std.Dev.	5.38	5.20	0.98

Metric Conversion: 1 mph = 1.61 km/h

Table 3-6. Speed Comparisons Between TP Sensors and Radar at Location C

Veh.No.	Radar	IRD	Abs.Diff.
1	42	42	0
2	48	49	1
3	44	44	0
4	44	44	0
5	39	40	1
6	48	48	0
7	43	44	1
8	40	41	1
9	46	48	2
10	42	43	1
11	44	42	2
12	42	42	0
13	44	44	0
14	48	48	0
15	47	46	1
16	47	48	1
17	48	50	2
18	47	47	0
19	42	42	0
20	50	51	1
21	35	35	0
22	35	35	0
23	54	55	1
24	45	45	0
25	46	47	1
26	43	43	0
27	46	46	0
28	41	46	5

Table 3-6. Speed Comparisons Between TP Sensors and Radar at Location C
(continued)

Veh. No.	Radar	IRD	Abs.Diff.
29	48	48	0
30	44	44	0
31	40	40	0
32	36	35	1
33	50	48	2
34	50	51	1
Mean	44.4	44.7	0.74
Std.Dev.	4.32	4.51	1.01

Metric Conversion: 1 mph = 1.61 km/h

utilized TP sensors at Locations B and C, respectively. Means and standard deviations compared favorably for all three sites, but especially at Locations A and C. Vehicle-specific speeds also compared closely. The number of same-vehicle speed comparisons where radar and IRD differences exceeded 3 mph (4.8 km/h) were only two at Location A, and one each at Locations B and C. For all three locations, there were vehicles compared for both lanes, and various types of vehicles were included. Vehicles were selected primarily because they were isolated and comparisons would be more accurate. Because many of the vehicles selected were not large trucks, these speed data cannot be compared with CTR speeds for this time period.

Tables 3-7 and 3-8 contain additional comparisons of data collected from the permanent sensors and radar on April 8, 1993. Comparing the mean of radar speeds and the mean of IRD speeds indicates that there is closer agreement for lane 1 than for lane 2. The difference in lane 2 mean values was 0.7 mph (1.1 km/h) while the difference for lane 1 was closer at 0.1 mph (0.16 km/h). This larger difference was probably due to greater difficulty in isolating target vehicles in lane 2 than in lane 1 in the gore area.

Roadside Sensors

Table 3-9 provides a comparison of speed data collected on May 5, 1993 from three sources: the CTR system, the IRD system using two inductive loops and one piezo sensor per lane, and radar. Even though this represents a small sample, it indicates very close comparison of both test systems with radar. The emphasis of this discussion is the accuracy

Table 3-7. Speed Comparisons Between Lane 1 Inductive Loops and Radar

Veh. No.	Speeds (mph)		
	Radar Gun	Ind. Loop	Abs. Diff.
1	51	55	4
2	59	57	2
3	58	57	1
4	43	44	1
5	50	49	1
6	53	50	3
7	56	57	1
8	57	52	5
9	56	56	0
10	53	54	1
11	57	57	0
12	54	55	1
13	52	61	9
14	54	57	3
15	57	61	4
16	50	42	8
17	53	55	2
18	57	57	0
19	42	44	2
20	62	61	1
21	48	54	6
22	54	46	8
23	56	57	1
24	57	57	0
25	55	55	0

Table 3-7. Speed Comparisons Between Lane 1 Inductive Loops and Radar (Continued)

Veh. No.	Speeds (mph)		
	Radar Gun	Ind. Loop	Abs. Diff.
26	72	72	0
27	56	55	1
28	55	52	3
29	56	57	1
30	59	57	2
31	48	48	0
32	53	55	2
33	60	61	1
Mean	54.6	54.8	2.2
Std. Dev.	5.31	5.76	2.42

Metric Conversion: 1 mph = 1.61 km/h

Table 3-8. Speed Comparisons Between Lane 2 Inductive Loops and Radar

Vehicle No.	Speeds (mph)		
	Radar Gun	Ind. Loop	Abs.Diff.
1	57	59	2
2	48	48	0
3	59	56	3
4	52	53	1
5	56	53	3
6	58	54	4
7	56	55	1
8	58	56	2

Table 3-8. Speed Comparisons Between Lane 2 Inductive Loops and Radar
(Continued)

Vehicle No.	Speeds (mph)		
	Radar Gun	Ind. Loop	Abs.Diff.
9	54	51	3
10	52	53	1
11	57	58	1
12	47	52	5
13	55	51	4
14	60	58	2
15	52	49	3
16	53	51	2
17	56	51	5
18	57	56	1
19	46	48	2
20	61	59	2
21	64	62	2
22	53	52	1
23	47	48	1
24	49	49	0
25	55	59	4
26	55	53	2
27	55	61	6
Mean	54.5	53.9	2.3
Std. Dev.	4.37	4.03	1.52

Metric Conversion: 1 mph = 1.61 km/h

Table 3-9. Speed Comparisons of CTR, IRD, and Radar

Vehicle No.	Speed (mph)		
	CTR	IRD	Radar
1	47	48	47
2	44	44	43
3	50	51	51
4	51	52	50
5	48	46	48
6	42	44	44
7	45	46	45
8	45	46	46
9	46	45	47
10	52	48	51
11	50	50	49
12	40	43	41
Mean	46.67	46.917	46.833
Std. Dev.	3.543	2.7826	3.0505

Metric Conversion: 1 mph = 1.61 km/h

of the three-beam CTR system compared to radar. Based on Table 3-9 and a larger sample of fifty-one same-vehicle comparisons of IRD output and CTR output (not shown), it is evident that the CTR system yields accurate speed data. The mean values of this larger sample are 46.76 mph (75.28 km/h) and 46.78 mph (75.32 km/h) for the CTR and IRD, respectively; the corresponding standard deviations are 3.78 mph (6.09 km/h) and 3.69 mph (5.94 km/h). Of these fifty-one paired comparisons, only four exceeded a speed difference of 3 mph (4.8 km/h).

One of the minor weaknesses of the CTR system when used on a two-lane ramp is the possibility of measuring two vehicles side by side. One example of this occurred during the time period of data collection on May 5, 1993. The IRD data reflect two five-axle tractor-semitrailers side by side, whereas the CTR system recorded a vehicle at the same time traveling at the same speed, but which was 96 feet (29.3 m) in length.

The CTR modified their system in November 1992 to give it the capability of activating a warning system for operators of trucks whose speeds exceeded the safe speed. When vehicles exceeding the dimensions (length and height) noted above entered the ramp exceeding the preset speed, the CTR system should have activated a warning device. In a small sample of seventeen observations on May 5, 1993, there were no errors observed in the results. In all cases where the length (according to CTR output) and speed (as monitored by both radar and the CTR system) exceeded the preset values, the warning system activated. By the same token, all other large vehicles with either speeds or dimensions less than preset values did not activate the system. Examples of vehicles that did not cause the system to activate were five-axle combination vehicles pulling unloaded flat-bed trailers.

COMPARISONS OF CTR SYSTEM AND IRD SYSTEM

TTI conducted speed and classification comparisons between the CTR roadside system and the on-pavement sensors. In applications involving two lanes and significant lane changing maneuvers, the CTR system holds an advantage because its measurements are not dependent on the lateral position of the vehicle. The CTR system can measure the speed and determine the length of a vehicle between lanes 1 and 2 as well as if the vehicle were centered in one of the lanes. The TTI sensors, on the other hand must sense the vehicle on all sensors in a lane in order to classify accurately. This capability is enhanced with inductive loops to determine presence. When piezo sensors alone were used at Location A, lane changing posed more of a problem than the current two-loop, one piezo set-up.

A minor weakness of the CTR system on a two-lane ramp is the possibility of two tall vehicles side-by-side. It might "see" only one vehicle and its speed and length measurements depend on the positioning of the two vehicles relative to each other. Fortunately, this is not a serious problem in that it usually errs on the conservative side. For example, the system might see two short vehicles (each under the threshold length) as one longer vehicle which meets the critical active message criteria. One conceivable exception is when a slow (safe vehicle) masks, or hides, a faster (unsafe) vehicle.

Two-Beam CTR System

Table 3-10 provides observed data from July 31, 1992 for comparing the CTR two-beam system with the IRD system to monitor speeds and lengths. The data comparison used a video recording to ensure the correct vehicles were being compared. CTR speeds were generally lower than those of the IRD system using temporary piezoelectric sensors. The mean value of speeds from the IRD system was 4.0 mph (6.44 km/h) higher than the mean of speeds from the CTR system. In the length determination, seven of the thirty-one vehicles recorded by the CTR system either could not be verified by the video tape or generate unreasonable lengths. The minimum length threshold set for this data set is not known.

Three-Beam CTR System

Many of the problems inherent in the early two-beam versions of the IR system were corrected by several modifications to both hardware and software and the resulting three-beam system of today. Table 3-11 provides a more recent comparison between the CTR

Table 3-10. Comparison of Two-Beam CTR and IRD Results

Veh. No.	Video Time	Vehicle Description	CTR System		IRD	
			Speed (mph)	Length (ft)	Speed (mph)	WB (ft)
1	14:22:10	3-S2 Gravel trailer	44	45	53	48
2	24:04	Van with ladder on top	59	8	--	--
3	24:30	SU-3 Gravel	48	17	51	18
4	25:09	SU-3 Gravel	42	14	59	18
5	25:11	Not able to verify	14	-1	--	--
6	25:41	3-S2 Gravel trailer	58	46	60	50
7	25:55	No vehicle passed but CTR system activated	47	10	--	--
8	26:42	SU-2 Flatbed hauling car	52	8	53	16
9	27:23	3-S2 van	44	55	46	51
10	27:50	Bobtail tractor	54	3	57	11
11	28:07	3-S2 (shifted lanes)	60	44	59	?
12	28:28	SU motor home	54	8	--	--
13	29:00	SU-2 propane gas truck	48	16	48	15
14	29:14	SU-2 van	47	7	51	11
15	29:29	SU truck with rack	53	18	64	14
16	32:11	3-S2 van, conv. cab	50	60	55	59
17	32:17	SU-2 with logs	48	13	50	12
18	32:18	Van with ladder on top	48	11	50	12
19	32:35	Pick-up with ladder	64	-1	--	--
20	33:20	3-S2 van	53	58	57	54
21	33:22	SU-2 with boom	50	23	55	18
22	33:36	Pick-up with 0_2 bottles	60	-1	--	--
23	34:34	3-S2 flat-bed (empty)	54	11	57	48
24	34:48	3-S2 van	49	59	50	48

Table 3-10. Comparison of Two-Beam CTR and IRD Results (Continued)

Veh. No.	Video Time	Vehicle Classification	CTR System		IRD	
			Speed (mph)	Length (ft)	Speed (mph)	WB (ft)
25	14:34:51	3-S2 van	35	49	46	55
26	35:37	3-S2 van	47	49	49	52
27	35:49	3-S2 van	58	49	61	51
28	36:26	SU-2 with load (changed lanes)	54	15	57	9
29	36:29	SU-3 dump	57	17	--	--
30	37:16	SU-3 solid waste	47	20	--	--
31	38:02	SU-3 oilfield	51	29	55	19
Mean			50.0		54.0	
Standard Deviation			8.89		4.80	

Metric conversion:
1 ft = 0.305 m
1 mph = 1.61 km/h

system and IRD output taken June 24, 1993. The systems being compared are the CTR three-beam system at the cabinet and the permanent sensors which utilized two inductive loops and one permanent piezoelectric sensor. Validation of these comparisons was accomplished by using a time lapse video cassette recorder and camera system mounted inconspicuously at the cabinet. A further modification to the CTR system installed in November 1992 provided the capability of generating an "alarm" when threshold conditions were exceeded by passing vehicles. The two criteria were vehicle speed and length. A subsequent modification provided a parallel signal to activate the camera and recording system each time an alarm was generated. The preset recording length for each passing vehicle was 15 seconds, which was sufficient viewing time to identify the vehicle and determine whether the system was functioning properly. Video recording quality in the 2-hour mode was generally sufficient to visually classify the vehicle. Unfortunately, if a vehicle passed which should have initiated the alarm and did not, the tape did not reveal the error. The IRD output was very helpful in verifying speeds and was generally helpful in verifying the vehicle lengths, but it did not detect vehicle heights as the CTR system did.

The time period covered by Table 3-11 data is approximately 1 hour, 40 minutes. The table only includes vehicles which were positively matched by the videotape. During this

Table 3-11. Comparison of Three-Beam CTR and IRD Results

Veh. No.	Time	CTR Speed (mph)	IRD Speed (mph)
1	12:07:58	58	58
2	12:16:30	47	48
3	12:17:13	48	50
4	12:20:47	52	53
5	12:21:58	49	53
6	12:24:00	48	50
7	12:25:40	50	54
8	12:25:55	55	63
9	12:26:09	52	50
10	12:28:06	52	52
11	12:30:12	55	54
12	12:30:29	54	57
13	12:30:42	51	52
14	12:31:56	52	54
15	12:32:09	51	50
16	12:34:30	57	61
17	12:35:34	55	57
18	12:35:55	48	50
19	12:37:26	50	50
20	12:38:02	52	52
21	12:40:11	52	50
22	12:44:03	53	54
23	12:44:11	49	51
24	12:47:16	49	53
25	12:48:34	46	50
26	12:49:07	48	50
27	12:51:14	52	54
28	12:53:50	53	54
29	12:55:18	57	56
30	12:55:40	48	48
31	13:00:28	55	58
32	13:03:55	50	53
33	13:04:22	54	53
34	13:07:53	50	53

Table 3-11. Comparison of Three-Beam CTR and IRD Results (Continued)

Veh. No.	Time	CTR Speed (mph)	IRD Speed (mph)
35	13:10:32	78	53
36	13:11:16	48	50
37	13:13:02	55	60
38	13:15:30	52	53
39	13:16:27	50	51
40	13:17:09	54	58
41	13:17:18	48	49
42	13:18:07	52	53
43	13:18:53	53	57
44	13:20:59	55	59
45	13:22:04	52	55
46	13:23:29	54	55
47	13:26:15	50	52
48	13:27:34	61	63
49	13:32:15	54	59
50	13:36:29	52	57
51	13:37:24	64	67
52	13:37:26	49	48
53	13:38:56	50	51
54	13:41:48	50	55
55	13:42:15	59	60
56	13:42:42	48	50
57	13:42:46	57	49
58	13:47:45	62	67
59	13:48:17	47	59
60	13:48:41	58	58
	Mean	52.7	54.2
	Std. Dev.	5.04	4.45

Metric conversion:
1 ft = 0.305 m
1 mph = 1.61 km/h

time period, the IRD system recorded seventeen large trucks which were not recorded by the CTR system. It was not possible to determine how many (if any) of these vehicles should have been detected by the CTR system. The CTR system generated a speed value on vehicle number 35 of 78 mph (126 km/h) which appears to be erroneous. The IRD classification for this vehicle was a five-axle tractor-semitrailer (American Association of State Highway and Transportation Officials designation 3-S2) with a wheelbase of 51 feet (15.5 m) and speed of 53 mph (85 km/h). The videotape verified that the vehicle was, in fact, a 3-S2. Even though the IRD system provided information missed by the CTR system, its output indicated some of its own deficiencies. During this time period of approximately 100 minutes, five trucks which were detected by the CTR system and verified by videotape were not detected by the IRD system.

CHAPTER 4. SUMMARY AND CONCLUSIONS

Table 4-1 provides a summary of the durability of TP sensors. At all three locations, the mean values for cable sensors are greater than for film sensors. The proportions of each pavement sensor type (film or cable) which endured at least a million axle load applications was approximately equal. This number was ten of nineteen for film sensors and seven of thirteen for cable.

Table 4-1. Summary Statistics on TP Sensor Durability

Location	Statistic	Sensor Type	
		Film	Cable
A	Mean	585783	892832
	Max.	1089099	2178198
	Min.	327840	16392
B	Mean	2217888	3246048
	Max.	5772384	4582656
	Min.	837216	572832
C	Mean	1324859	3776316
	Max.	2062184	7332312
	Min.	229131.5	211509

Another way of considering the durability is strictly by time, although this ignores factors that are thought to influence sensor life. For these sensors to be viable in monitoring traffic on freeway ramps, they must last at least a year or longer. On this ramp, only three film sensors lasted a year or longer, and only four cable sensors lasted a year or longer. These results might be even worse as traffic volumes, and especially the number of trucks, increase.

Table 4-2 provides a summary of tabulated comparisons above. Comparisons of speed values from radar and the IRD system using both TP and inductive loops indicates reasonably close comparisons of sample means. Also, differences appear to follow a random pattern; that is, the test system is both higher and lower than the radar speed sample means. Comparison of the CTR sample means, on the other hand, indicates that its sample means are consistently lower than the IRD sample means and by a larger magnitude than in the IRD versus radar comparison. Standard deviations of CTR output speed data were always higher than IRD. Comparisons of the two-beam and three-beam CTR infrared beam systems indicates significant improvements in consistency as a result of software and hardware modifications during the time period of this study.

Table 4-2. Summary of Sensor Comparisons

Sensors Tested	Loc.	Sample Size	Speeds (mph)			
			Radar or CTR		IRD	
			Mean	s	Mean	s
TP Piezo & Radar Date: 8/11/92	A	18	53.1	6.01	53.3	5.45
	B	10	44.6	3.50	42.9	3.23
	C	19	43.1	6.56	42.8	6.41
Ind. Loop & Radar La 1-2 TP Piezo & Radar (B&C) Date: 9/15/92	A	45	54.7	7.69	54.8	7.76
	B	36	47.0	5.38	48.4	5.20
	C	34	44.4	4.32	44.7	4.51
Ind. Loop & Radar La. 1	A	33	54.6	5.31	54.8	5.76
Ind. Loop & Radar La. 2	A	27	54.5	4.37	53.9	4.03
TP Piezo & CTR 2-Bm.	A	31	50.0	8.89	54.0	4.80
TP Piezo & CTR 3-Bm	A	60	52.7	5.04	54.20	4.45

Metric conversion:
1 mph = 1.61 km/h

The CTR sensor system, by its very nature, has inherent advantages over a pavement based system. It is less intrusive to the traffic stream during installation and maintenance and provides information on vehicle (or load) height and length that is essential in identifying high center-of-gravity loads which are subject to rollover due to excessive speed. Also, it more accurately monitors vehicles changing lanes near the sensors than the pavement based systems. Finally, the infrared system is a relatively low-cost system.

Disadvantages of the roadside system include difficulties of maintaining alignment of beams on structures where vibrations are a problem, monitoring multiple vehicles side by side on multi-lane roadways and missing a few high center-of-gravity loads which do not meet the criteria of length and height. In its current configuration, it requires a constant AC power source. For future applications, it should be equipped with its own power source and further modified to make it a stand alone system which could operate several days or even weeks without needing attention.

REFERENCES

1. Traffic Monitoring Guide, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., June 1985.

2. Garner, J.E., Clyde Lee and Liren Huang, Infrared Sensors for Counting, Classifying, and Weighing Vehicles, Final Report, Center for Transportation Research, the University of Texas at Austin, for Texas Department of Transportation, 1990.

APPENDIX

Table A-1. Default TCC 500 Axle Classification (Scheme "F")

Classification (Bin Number)	Vehicle Type
F1	Motorcycles (Optional)
F2	Passenger Cars
F3	Other Two-Axle, Four-Tire Single Unit Vehicles
F4	Buses
F5	Two-Axle, Six Tire, Single Unit Trucks
F6	Three-Axle, Single Unit Trucks
F7	Four or More Axle, Single Unit Trucks
F8	Four or Less Axle, Single Trailer Trucks
F9	Five-Axle, Single Trailer Trucks
F10	Six or More Axle, Single Trailer Trucks
F11	Five or Less Axle, Multi-Trailer Trucks
F12	Six-Axle, Multi-Trailer Trucks
F13	Seven or More Axle, Multi-Trailer Trucks