Technical Report Documentation Page

1. Report No. FHWA/TX-99/1715-1	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
INITIAL EVALUATION OF THE EXISTING TECHNOLOGIES FOR VEHICLE DETECTION

5. Report Date
October 1997

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.
Research Report 1715-1

9. Performing Organization Name and Address
Texas Transportation Institute
The Texas A&M University System
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.
Study No. 0-1715

12. Sponsoring Agency Name and Address
Texas Department of Transportation
Research and Technology Transfer Office
P. O. Box 5080
Austin, Texas 78763-5080

13. Type of Report and Period Covered
Interim:
September 1996 - August 1997

14. Sponsoring Agency Code

15. Supplementary Notes
Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Study Title: Evaluation of Innovative Methods to Reduce Stops to Trucks at Isolated Intersections

16. Abstract

Most vehicle detection today relies on inductive loop detectors (ILDs). However, problems with installation and maintenance of these detectors have necessitated evaluation of alternative detection systems. Replacing ILDs with better detectors requires a thorough evaluation of the alternatives. This evaluation included examination of the functional quality, reliability, and cost of these technologies as well as development of application of recommendations. The work plan for this study consisted of eight specific research objectives; the three included in this report are: a literature search; a survey of Texas and other states; and an evaluation of existing technologies for vehicle detection. Primary detection technologies included in this study are: video image detection systems (VIDS), passive infrared, active infrared, passive magnetic, radar, Doppler microwave, passive acoustic, and ILDs. Results of new detector testing clearly indicate promising alternatives to ILDs, but the limitations of these new detectors must also be accepted. Researchers found that some technologies performed quite well, while, in some cases, offering features that are more flexible than ILDs. These technologies include: VIDS, passive infrared, active infrared, radar, Doppler microwave, and pulse ultrasonic.

17. Key Words
Non-intrusive Detectors, Sensor Technologies, Vehicle Detection, Inductive Loop Detectors

18. Distribution Statement
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National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 112	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

INITIAL EVALUATION OF THE EXISTING TECHNOLOGIES FOR VEHICLE DETECTION

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Research Report 1715-1
Research Study Number 0-1715
Research Study Title: Evaluation of the Existing Technologies
for Vehicle Detection and Establishment of Communication Data Requirements

Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

October 1997

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IMPLEMENTATION STATEMENT

The objective of this research study is to evaluate new detector technologies through a literature search and a survey of Texas Department of Transportation (TxDOT) districts and out-of-state agencies. The implementation recommendations for this project will be presented in the final report.

DISCLAIMER

ACKNOWLEDGMENT

The authors wish to gratefully acknowledge the contributions of several persons who made the successful completion of this research possible. This especially includes the project directors, Mr. Abed Abukar and Ms. Lilly Banda. Special thanks are also extended to employees of all the Texas Department of Transportation districts that participated in the survey, as well as personnel of out-of-state agencies who participated.

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SUMMARY

Most vehicle detection today relies on inductive loop detectors (ILDs). However, problems with installation and maintenance of these detectors have necessitated evaluation of alternative detection systems. Replacing ILDs with better detectors requires a thorough evaluation of the alternatives. This evaluation included examination of the functional quality, reliability, and cost of these technologies as well as development of application recommendations.

The work plan for this study consisted of eight specific research objectives including: a literature search; a survey of Texas and other states; an evaluation of existing technologies for vehicle detection; an interim research report; a comparison of the functional quality and reliability of loops versus other detection technologies; a cost analysis of various vehicle detection technologies; evaluating and developing a standardized data exchange protocol for the transmission of vehicle detector information; a recommendation of technologies for appropriate applications; and a project summary report. This is an interim report, which addresses the first three research objectives.

TTI gathered information for this study by conducting a comprehensive literature search and a telephone survey. The literature review included approximately 450 documents that were initially identified as possible sources and were reviewed for relevance. The survey included all 25 TxDOT districts and 15 out-of-state agencies. Its purpose was to determine the state-of-the practice in both the existing ILD usage and effectiveness of the new non-intrusive detectors.

This report organizes findings on individual detectors according to the source: literature, TxDOT district experience, and out-of-state agency experience. Each detection technology has its own section, providing the experience of all available sources in a concise format. The literature section provides results primarily from other field testing by the Minnesota Guidestar Program and the Hughes Aircraft Company. The primary detection technologies are: video image detection systems (VIDS), passive infrared, active infrared, passive magnetic, radar, Doppler microwave, passive acoustic, and ILDs.

There is little doubt as to the need to find detection technologies offering replacement potential for the traditional ILD. However, loops are a mature technology, having been in use for many years, so transportation engineers should not expect newer non-intrusive detectors to initially replace loops in all cases. Results of new detector testing clearly indicate promising alternatives to ILDs but the limitations of these new detectors must also be accepted.

VIDS appears to be a likely candidate to replace ILDs in some situations, and early problems such as shadows, changing light conditions, and double counting headlights at night are being addressed. The California Polytechnic State University evaluated eight video image detection systems in field performance tests a few years ago. Evaluation results indicated that most systems generate vehicle count and speed errors of less than 20 percent over a mix of low, moderate, and high traffic densities under ideal conditions (*22*). Parameters that reduced the

accuracy of these systems included transitional light conditions during sunrise and sunset. This was of significant concern because these time periods may occur during the heaviest traffic flow. Another series of evaluations found that the VIDS provided the best performance in the areas of detection, speed estimation, and vehicle classification. However, VIDS had limitations in poor lighting and certain weather conditions, and was the most expensive sensor tested *(33)*. Recent testing in the Minnesota Guidestar program discovered that the Eliop Trafico EVA 2000 detection system was capable of very accurate freeway counts, within 1 percent of the baseline. Calibration of this system was difficult as a result of a complicated user interface; however, the system was not adversely impacted by any weather condition and was the only video system that was not affected by light transitions. The EVA 2000 was not recommended for intersection applications so the researchers did not supply intersection results.

The Minnesota DOT and SRF Consulting tests also included other non-intrusive traffic detection technologies besides VIDS. The technologies were tested at the Minnesota site in a wide range of weather, lighting, traffic, and geometric conditions (*28*, *29*, *30*). Researchers found that the following technologies performed quite well: passive infrared, active infrared, radar, Doppler microwave, and pulse ultrasonic.

Duckworth determined that pulsed ultrasonic was the best sensor for detection and classification when cost, the communications bandwidth requirements, and processing power are considered. Radar was the best velocity sensor for vehicles it detected. The researchers recommended that a combination sensor of pulsed ultrasound and either pulsed-Doppler ultrasound or Doppler radar be considered as the strongest candidate as an inexpensive replacement of ILDs (*33*). According to tests by Hughes Aircraft Company, Doppler microwave detectors provided the best performance for gathering specific data for most categories, however this technology does not detect stopped vehicles. The Doppler microwave, true presence microwave, VIDS, and ILDs performed well for high volume counts. The Doppler microwave was the best performing technology for low volume speed and for high volume speed. The Doppler microwave, true presence microwave, magnetometer, and inductive loop technologies performed best in inclement weather *(31)*.

Based on the literature review, the survey of districts and out-of-state agencies, and field testing in other ongoing research endeavors, the research team recommends additional testing of a few detectors. These include a relatively new VIDS product called TrafficVision, by the Nestor Corporation, a microwave detector called Accuwave, and a radar detector, the RTMS by Electronic Integrated Systems.

1.0 INTRODUCTION AND METHODOLOGY

1.1 OVERVIEW

Traffic management is becoming more active in the operation of the highway transportation infrastructure. Effective traffic management begins by accurately detecting vehicle presence. Vehicle detection appears to be the weakest link in advanced traffic applications and automatic surveillance of Intelligent Transportation Systems (ITS). Most vehicle detection today relies on inductive loop detectors (ILDs). However, problems with installation and maintenance of these detectors have made it necessary to evaluate alternative vehicle detection systems. Given that there are a number of different technologies and various products within technological categories being used by the Texas Department of Transportation (TxDOT), it is essential to develop a standard statewide protocol for integration with existing and proposed traffic management systems.

Replacing ILDs with better detectors requires a thorough evaluation of the alternatives. This evaluation includes an examination of the functional quality, reliability, and cost of these technologies as well as development of application recommendations.

1.2 RESEARCH FOCUS

This research evaluated the existing technologies for vehicle detection, thereby determining strengths and weaknesses of competing systems. This research study provides TxDOT decision makers with selection criteria when installing detection systems. This selection criteria includes: cost, parameters measured, accuracy, and limitations for use in both freeway and intersection applications. The development of data exchange requirements by this research has the potential of greatly decreasing the complexity of data and improving interpretation of data arriving at a central traffic operations center or even on a smaller scale. The common data protocol also benefits the department in comparing each system against its competitors.

1.3 RESEARCH OBJECTIVES

The work plan for this study consisted of eight specific research objectives including: a literature search; a survey of Texas and other states; an evaluation of existing technologies for vehicle detection; an interim research report; a comparison of the functional quality and reliability of loops vs other detection technologies; a cost analysis of various vehicle detection technologies; evaluating and developing a standardized data exchange protocol for the transmission of vehicle detector information; a recommendation of technologies for appropriate applications; and a project summary report.

This research report, which is an interim report, addresses the first three research objectives, which are detailed below. The intent of the report is to document and provide an evaluation of existing technologies within TxDOT and other transportation agencies.

1.4 METHODOLOGY

A detailed description of the approach the research team used to accomplish the objectives addressed in this report are presented below.

1.4.1 Literature Search and Review

A comprehensive literature search was conducted to identify publications and reports on various technologies that are currently available for vehicle detection. Detection was assumed to be for "permanent" or long-term continuous vehicle monitoring. This search, using key words and phrases, utilized the following catalogs and databases: Texas A&M University's Sterling C. Evans Library NOTIS (local library database), Wilson's Periodical Database, FirstSearch, National Technical Information System (NTIS), and Transportation Research Information Service (TRIS).

Sterling C. Evans Library is a major local source of information with holdings of more than 2 million volumes of books, 4.3 million documents and microforms, 12,000 current periodical titles and holdings for more than 28,000 serial titles. FirstSearch is an electronic information system designed to provide access through the Online Computer Library Center (OCLC) national database. The database contains more than 34 million bibliographic records representing the holdings of 22,000 libraries in more than 63 countries, and to Article First and Contents First which index 11,000 journals. NTIS is a CD-ROM database which provides bibliographic records of published scientific and technical information. TRIS is a worldwide source of information on various modes and aspects of transportation including planning, design, finance, construction, equipment, traffic, operations, management, marketing, safety, and other topics. It contains more than 315,000 abstracts of completed research, summaries of research projects in progress, and selected articles from more than 1,000 journals. TRIS also includes access to TLIB (Transportation Library Subfile) which is the bibliographic citations of the new acquisitions of the Institute of Transportation Studies Library at the University of California, Berkeley, and the Northwestern University Transportation Library at Evanston. TLIB covers all modes of transportation and provides an annual input of more than 9,500 records to TRIS.

Key words and key word combinations were selected to conduct a systematic search of the above databases. Some of the key words and key word combinations used in the search included: vehicle detection, non-intrusive technologies, non-intrusive vehicle detection, traffic data collection, detection technology, traffic monitoring, vehicle sensors, ITS infrared sensors, magnetic sensors, radar, microwave, ultrasonic sensors, acoustic sensors, video sensors, inductive loops, presence detectors, vehicle detectors, traffic sensors, video imaging, video detection.

Approximately 450 documents were identified as possible sources and were reviewed for relevance. The literature review is discussed in detail in chapter 2.

1.4.2 Survey of State Practices

A survey of TxDOT districts and of various states was conducted to determine what equipment is being used or has been purchased for vehicle detection. The initial question asked was:

> *"What vehicle detection technologies are currently being used in (name of jurisdiction) either for signal control or on freeways?"*

A positive response to this question was followed by a question on issues including: where the system was located, the appropriate person to contact regarding its functionality, and the availability of data on the cost, accuracy, and durability of the system. A detailed discussion of the results of this survey can be found in chapter 3 of this report and a copy of the survey can be found in the Appendix.

1.4.3 Evaluation of the Existing Technologies for Vehicle Detection

TTI utilized the findings of the literature review and the survey of TxDOT districts and states and conducted a thorough evaluation and comparison of the traffic monitoring devices being used. TTI identified strengths and weaknesses of the various systems identified, based on the available data. Because of TTI's current knowledge base and the documentation already available on the more prominent devices being used today, this evaluation was viewed as an update, searching for new devices that have potential for application. For devices recently released into the vehicle detection market, there will be little available information and data with which to compare. As an example, the Peek VideoTrak™ 900 system was recently released late in CY 1995, therefore extensive data regarding this system is not yet available. For other systems, such as the Autoscope, there will be a more definitive data set with which to make quantitative comparisons. For example, the Road Commission of Oakland County (RCOC), Michigan began installing Autoscope video image detection systems (VIDS) systems in 1991 as part of a multiyear operational test that is anticipated to include a total of 800 intersections. This is the largest and most complex Autoscope (or other VIDS systems) application to date (*1*). TTI has made contact with the appropriate representatives in recent research to obtain the necessary information for an evaluation. The detailed evaluation of existing technologies can be found in chapter 4.

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Traffic detection has been utilized to obtain useful traffic information for many years. In the 1920s manual traffic signals were replaced by pretimed signals and the need to obtain traffic detection and traffic data collection was realized. One of the first detectors was a pressure sensitive, treadle type of detector that was installed in the road and detected vehicles when they passed over the plates (*2*). Pneumatic tubes, "electric-eye" optical, and magnetic detectors were used in the 1930s. By the 1960s inductive loop, infrared, ultrasonic, radar, and photoelectric systems were being used, with the inductive loop system becoming the predominant system by the 1970s (*3*).

Detectors recognize the presence of a stopped or moving vehicle and identify the passage of the vehicle by completing a circuit or detecting changes in an electrical or magnetic field. Most types of detectors are composed of three components: the sensor, the lead-in cable, and the interpreter/receiver (*4*). Detectors also collect or derive traffic volumes, vehicle speed, lane occupancy, density, and queue lengths. These parameters are used to predict or derive levels of congestion, incidents, and delays. Successful implementation of automatic detection and control systems is dependent on the systems's reliability (*5*).

2.2 DETECTOR CATEGORIES

Detectors can be generally categorized as either intrusive or non-intrusive. Intrusive detector systems require intrusion into or onto the pavement or roadway during installation. Examples of intrusive detectors are inductive loops and road tubes. Non-intrusive detector systems eliminate interference with traffic operations for the most part, because they do not need to be installed into or on the roadway. Non-intrusive systems are installed over the roadway, on the side of the roadway, or beneath the pavement by pushing the device in from the shoulder (*6*). Examples of non-intrusive systems are video systems, infrared devices, and acoustic systems.

Non-intrusive detector systems are currently increasing in prominence due to today's congested freeways and signalized intersections, because they reduce interference with traffic operations during installation and maintenance procedures. They can also be used on bridge decks, where installation of intrusive detector systems is prohibitive due to possible weakening of the structure.

2.3 DETECTOR TYPES

The majority of vehicle detection today is accomplished using inductive loop detectors. Other common detectors include: magnetometers, piezoelectric sensors, and photoelectric sensors. Video imaging detection systems are increasing in prominence as well as other developing systems that are mounted above the roadway. Brief descriptions of some of the existing devices and the most promising new innovations are provided below.

2.3.1 Inductive Loop Detector

The inductive loop detector is composed on one or more turns of insulated loop wire installed in a shallow slot that is sawed in the pavement, a lead-in cable, and a detector electronic unit. Induction can be characterized as producing a change in a body without physical contact with the body (*7*). Electrical induction in a traffic signal system is comprised of a detector unit that passes a current through the stranded loop wire, thereby creating an electromagnetic field around the wire. Moving a conductive metal object, such as a vehicle, through this field disturbs the electromagnetic field, producing a change in energy level. As the vehicle enters the electromagnetic field of the loop, it causes a decrease in the inductance of the loop and an increase in the oscillation frequency. The inductive loop detector, which was introduced in the 1960s, continues today as the most commonly used form of detector, even though its weaknesses are widely recognized.

Proper installation of the loop in the road surface is important to improve the reliability of the system. Some pavement surfaces, such as bridge decks, preclude the saw cutting necessary to install permanent inductive loop detectors. A primary disadvantage of inductive loop detectors is the expense of relocating or repairing loops after installation. This procedure requires extensive traffic control and results in congestion and motorist delay (*8*). Traffic control costs and delay costs for loop installations make loops less competitive than their newer detector counterparts. Detector "cross-talk" and increased pavement stress are two additional disadvantages of inductive loop detector systems. Additionally, there are several adverse conditions that affect the operation of ILDs. These conditions include high voltage power lines under the pavement, a pavement subsurface with a high iron content, and unstable pavement conditions. Underground wires, conduit, and pull boxes are susceptible to being damaged by other utility work. Modern detection equipment can overcome the first two conditions, but changing or unstable pavement conditions result in increased maintenance costs (*9*). One advantage of ILD systems is their ability to operate in all weather and lighting conditions (*8*).

There are diverging opinions on the reliability of inductive loop systems. Some agencies believe that inductive loop technology is the best available, while others claim that inductive loop detectors malfunction so frequently that they are simply not worth repairing (*3*). One study that interviewed several California Department of Transportation personnel, indicated that only one-half of the inductive loop systems installed are currently in operation. In this same study, Illinois Department of Transportation personnel stated only 5 percent of the inductive loop systems in their jurisdiction are inoperable at any given time. Illinois officials attribute this success to an active maintenance program which monitors each loop (*3*). Such programs are costly, but maintaining a low failure rate requires them.

Bikowitz et al. (*10*) analyzed 15,000 inductive loop detectors in New York State and found that loop failures were mainly caused by either improper installation, inadequate loop sealants, or wire failure. The study revealed several installation processes needed revision to improve the inductive loop detector's reliability. Improper saw cutting techniques, loop wire splicing, and inadequate loop sealant bonding resulted in loop wire breakage.

A study by Chen et al. (*5*) conducted in Los Angeles revealed that up to 15 percent of the 115 detectors analyzed were unavailable, and between 2 and 11 percent showed error flags during the experiment. The causes of the detector failures included: moisture, loop sealant deterioration, pavement cracking, broken wires, deteriorated insulation, corroded splices, and detuned amplifiers.

2.3.2 Microloop Detection Systems

A microloop detection system is a passive sensing system that is based on the earth's magnetic field. When a vehicle passes through the detection zone, it temporarily distorts the earth's magnetic field. This magnetic field change creates an electrical circuit change in a specially designed circuit in the microloop. Advantages of using microloop detection systems include speed of installation, installation below the pavement in the subgrade, and less wire needed to create the loop. Disadvantages of microloop systems include installation difficulties and the narrow effective width of the detection field, thereby requiring several probes to detect a variety of design vehicle types (*9*).

2.3.3 Magnetometers

A magnetometer consists of an intrusive sensor about the size and shape of a small can, a lead-in cable, and an amplifier. The cylinder portion of the magnetometer contains sensor coils that operate in a manner similar to inductive loops. These coils are installed in a small circular hole in the center of each lane and communicate with the roadside by wires or radio link. Magnetometers function by detecting increased density of vertical flux lines of the earth's magnetic field caused by the passage of a mass of ferrous metals, such as in a vehicle. They operate in either presence or pulse modes and are embedded in the pavement. Magnetometers are more durable than loop sensors, require less cutting of the pavement, are easier to install, and can be installed underneath bridge decks without damage to the deck. The disadvantages of magnetometers are similar to those of inductive loop detector systems, in that they sometimes double count trucks, and are less likely to detect motorcycles due to the vehicle's small detection zone (*3*).

2.3.4 Magnetic Detector Systems

Magnetic detectors consist of several dense coils of wire wound around a magnetic core. This core is then placed in or underneath the pavement. Magnetic detector systems operate in the same manner as magnetometer detector systems and inductive loop detectors (*11*). One disadvantage of magnetic detector systems is their inability to detect stopped vehicles; because detection requires motion. Another disadvantage occurs when two magnetic detectors are placed close together, this placement can result in interference between the two detectors (*6*).

2.3.5 Piezoelectric Sensors

Piezoelectric sensors are a film fabricated using a crystalline form of long hydrogen, carbon, and fluoride polymer molecular chains. The crystalline chain produces an electrical charge when a mechanical strain occurs as a result of a vehicle passing over the film (*12*). Piezoelectric sensors have been effectively used in vehicle detection, both as axle sensors for vehicle classification and for weigh-in-motion applications for truck weight data collection.

The first piezoelectric effects were documented over 100 years ago when it was observed that quartz crystals produced an electrical charge when deformed. It was also noted that the crystals changed shape when they were placed in an electric field. Later research at the Massachusetts Institute of Technology discovered that certain ceramics could be polarized to induce piezoelectric properties. The term "piezoelectricity" derives from the Greek for "pressure electricity." In straightforward terms, it is the material's ability to transform mechanical energy into electrical energy; or in other words, piezo sensors are transducers. Piezoelectricity can be defined as "electric polarization produced by mechanical strain in certain crystals, the polarization being proportional to the amount of strain and changing sign with it" (*13*).

One advantage of piezoelectric sensors is their ability to be utilized as weigh-in-motion detectors. Piezoelectric sensors serve as axle sensors, so they can be used to distinguish between vehicle types (*8*, *12*). Modern vehicle classifiers typically use a combination of piezoelectric sensors and inductive loop detectors to count and classify vehicles in a user-definable classification scheme. Undesirable features of piezoelectric sensors include: weakening of the pavement due to required cutting, less than desirable sensor durability, reduction in sensor life due to resurfacing, and sensitivity to moisture penetration if damaged. In recent years piezoelectric sensors are becoming more extensively used in the United States.

2.3.6 Photoelectric Sensors

Photoelectric sensors have been used since the 1950s. When a sufficient amount of 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 a longer life span and durability under harsh conditions. Probably the biggest advantage of LEDs is their ability to be modulated thousands of times per second. LEDs operate in several visible-light wavelengths as well as in infrared wavelengths. However, infrared LEDs are often preferred because they emit more light intensity than visible-light LEDs and because most photo detectors are more sensitive in the infrared range. One disadvantage of infrared LEDs when compared to visible light LEDs is greater difficulty of alignment (*14*).

2.3.7 Microwave and Radar Sensors

Microwave detection sensors utilize a microwave energy beam directed onto a detection area from an antenna located either along the side or above the roadway. The antenna is angled toward the traffic flow, thereby creating a Doppler effect when the signal is reflected The signal sent by the system is intercepted by the vehicle and reflected or echoed back to the sensor (*3*). According to the Doppler principle, the motion of the vehicle causes a frequency change in the reflected signal that is known as a Doppler phase shift. This phase shift is recognized by the detection system and is used to detect the movement of vehicles and collect speed data. The operating frequency of the signal is normally in the K-band (24 gHz) or the X-band (10 gHz) (*15*).

Radar detectors have been commercially available for years and use a pulsed energy beam. The beam, which is either frequency-modulated or pulse-modulated, detects vehicles by determining the time delay of the reflected signal. This information is used to calculate the distance of the vehicle. Newer radar detectors promise to give both presence and passage detection as opposed to previous units that detected passage only. In 1991 the manufacturer's initial unit costs ranged from $1,000 to $4,000 depending on unit features. The manufacturer's claims indicated life cycle costs were comparable to inductive loops. Current radar sensors for freeway applications have the ability to detect vehicles, produce traffic counts, and provide speed data across one to three lanes.

Microwave and radar detection systems are simpler to install and maintain than inductive loop systems. A principal disadvantage of microwave and radar systems is the inability to detect a stopped vehicle and to measure occupancy (*3*). In the past, radar systems have been vulnerable to vandalism (*2*). Microwave and radar systems are also expensive to purchase and operate due to Federal Communication Commission (FCC) licensing requirements (*11*).

2.3.8 Lasers

"Light Amplification by Stimulated Emission of Radiation" devices, also known as lasers, contain a crystal, gas, or other material in which atoms are stimulated by focused light waves. The laser unit is mounted either above or beside the roadway. The receiver is built into the transmitter, and actuations are detected by changes in the characteristics of the laser beam. This very narrow beam can be aimed more precisely than either the infrared or ultrasonic devices, thereby avoiding false actuations from vehicles in adjoining lanes. One disadvantage of the laser system is that small vehicles, such as motorcycles, traveling on the edge of a lane may be missed when using this narrow beam (*11*).

2.3.9 Ultrasonic Detector Systems

Ultrasonic detection systems consist of compact electronic signal generation and receiver units that are mounted either above or beside the roadway. A vehicle is detected when the energy burst that is directed at a target point is reflected faster than expected. Ultrasonic detectors can be used for both presence and pulse applications. Labell et al. (*3*) compared ultrasonic detectors with inductive loop detectors and concluded that the flow accuracy was very similar to that of inductive loops. However, occupancy and speed measurements from ultrasonic detectors were very different from those generated by loops. One possible explanation of speed variation is that speed is calculated from occupancy, a parameter that is inaccurate. Another part of the study compared ultrasonic detectors with visual counts. In this case, the data collected by ultrasonic detectors closely matched the visually counted data. Modifications have since resulted in improvements to ultrasonic detectors, reducing some of the above problems.

One disadvantage of ultrasonic sensors is that environmental conditions can affect their operation. Ultrasonic detectors also require a very high level of specialized maintenance. Studies of ultrasonic detectors also revealed problems with controlling the conical detection zone and in some situations found that the conical detection zone may miss vehicles (*3*).

The most extensive use of ultrasonic detectors is on surface streets and freeways in Japan, where government policy precludes cutting the pavement. These detectors are a major component of the Tokyo traffic control system. A central computer monitors traffic signals and vehicle motion based on these systems throughout Tokyo and then relays real-time information to motorists and police. A disadvantage of these sensors, as noted in a 1994 IVHS America presentation, is the inability to directly measure speed (*16*). Therefore, their use in future IVHS (now ITS) applications in Japan and elsewhere is anticipated to be limited. The state of New York continues to use ultrasonic detectors in remote areas with bad pavement. They estimate that 10 percent of their highway surveillance is provided by ultrasonic detectors (*15*). The Illinois DOT replaced its ultrasonic detectors with inductive loop detectors because the ultrasonic detectors were less reliable and less cost effective than inductive loop detectors (*3*).

2.3.10 Active Infrared Detection Systems

Active infrared sensors operate by focusing a narrow beam of energy onto an infrared-sensitive cell. Detections occur when vehicles pass through the beam and interrupt the signal. The infrared beam can be transmitted from one side of the road to the other, or from an overhead or roadside position to a device on the pavement surface. Infrared systems can provide information on vehicle height and length, in addition to simply passage of vehicles, at a relatively low cost. These sensors can be used as either presence or pulse sensors.

Preliminary testing by public agencies indicates very promising results for monitoring vehicle speeds and classifications. Active infrared systems appear to be able to operate during day/night transitions and other lighting conditions without significant problems. An advantage of the infrared sensor is the minimal disruption to traffic during installation or maintenance. The infrared sensor can be placed at the roadside or overhead on sign structures (*11*). The only weather conditions that appear to be problematic for this device are heavy fog and heavy dust. Disadvantages of infrared sensors include: difficulties of maintaining alignment on vibrating structures; limitations of across-the-road applications to one-lane roadways; inconsistent beam patterns caused by changes in infrared energy levels due to passing clouds, shadows, fog, and precipitation; lenses used in some devices may be sensitive to moisture, dust, or other contaminants; and the system may not be reliable under high volume conditions. For multilane applications, infrared detectors should be mounted overhead for both speed and volume measurements (*11*). Infrared detectors are used extensively in England for both pedestrian crosswalks and signal control. Infrared detections systems are also used on the San Francisco-Oakland Bay Bridge to detect presence of vehicles across all five lanes of the upper deck of the bridge, thereby providing a measure of occupancy (*15*).

2.3.11 Passive Acoustic Detection Systems

Passive acoustic detection systems are generally composed of an array of microphones that are aimed at traffic and "listen" for passing vehicles. A passive acoustic device, developed in partnership with the U.S. Navy, is a recent addition to the inventory of non-intrusive detectors. The major components of this sensor system include a controller card, from one to four independent acoustic sensors (microphones), and interconnect cables. The SmartSonic TSS-1, currently marketed by International Road Dynamics, provides a detection zone size of 1.8 m to 2.4 m (6 ft to 8 ft) in the direction of traffic, and provides one or two lane selectable zone size in the cross lane direction. The TSS-1 processing in the controller card has the capability of computing traffic flow measurements such as vehicle volume, lane occupancy, and average speed for a selectable time period. No accuracy data were available except for speeds.

In limited testing, the speed accuracy for the acoustic detection system was plus-or-minus 10 percent when compared to inductive loop detection systems. The system does not currently classify vehicles; however, addition of this feature is planned. Power requirements for the system is low, 5 to 6 watts, which will allow the use of solar panels. The cost of the acoustic sensor is $1,450 per unit, with one required per lane per detection location. The detection system also requires a controller card at a cost of $800. Each card can accommodate up to four acoustic sensors. The system which can be mounted in either a sidefire or overhead configuration has minimum mounting requirements of 6.1 m (20 ft) overhead and 7.6 m (25 ft) horizontal distance from the travel lane. Available information indicated that weather conditions, other than very dense fog, do not interfere with the system detection capabilities.

2.3.12 Automatic Vehicle Identification Systems

Automatic Vehicle Identification (AVI) technology utilizes a transponder inside the vehicle and a radio frequency signal unit located along side or above the roadway. The transponder receives a signal from the roadside unit and responds with an encoded signal uniquely identifying information about the driver or vehicle. A transponder card reader, part of the radio frequency unit, then processes this information. AVI systems are capable of uniquely identifying a vehicle passing through the detection area. This technology has a variety of uses as ITS technology advances including electronic toll collection (*11*). Electronic toll collection systems debit a special account when a vehicle passes through the toll booths. A related application for AVI systems is congestion pricing (*17*).

AVI systems monitor traffic conditions by using vehicles as probes in the traffic stream. The AVI system tracks a "tagged" vehicle along a freeway, allowing data to be processed at a single point location, as well as over lengths of roadway. The system utilizes "read-write" capabilities that provide two-direction information flow and information storage by the transponder. Information stored upstream on the vehicle's transponder is then read at the next card reader location, allowing the AVI system to track a vehicle along the roadway (*17*). An AVI system can record headway, volumes by lane and by station, the number of tagged vehicles passing in each lane at a reader station, and the number of tagged vehicles that switch lanes between stations. A sophisticated system may also relay vehicle type, driver-input origin and destination information, and travel speed based on the vehicle's speedometer (*17*). The major disadvantage of using an AVI system as a vehicle detection system stems from the limited number of vehicles equipped with transponders.

2.3.13 Video Image Detection Systems

Video image detection research evolved during the mid 1970s. Early systems used "fixed geometry" sensors, meaning that points on the roadway being monitored could not be changed unless the camera was physically moved. This feature was undesirable, so subsequent generations of video image systems were developed to allow alteration of the detection area within the camera's field-of-view through the use of video image detection software. Real-time detection also became available with these technological advances (*18*, *19*). A video image detection system consists of one or more cameras providing a clear view of the area, a microprocessor-based system to process the video image, and a module to interpret the processed images (*11*). Advanced video image detection systems can collect, analyze, and record traditional traffic data; detect and verify incidents; classify vehicle types; and monitor intersections (*20*). Video image systems have evolved through the following three classes of systems: tripwire, closed loop tracking, and data association tracking.

Tripwire systems, which were the first generation of video image detection systems, are the least demanding in terms of computer power and speed. These systems operate by allowing the user to define a limited number of detection zones in the video camera field of view . When a vehicle enters a detection zone, it is identified in a manner analogous to inductive loops. In fact, tripwire systems are the functional equivalent of inductive loop systems and are intended to replace inductive loops in areas where a large number of loops are employed. Most of the video image detection systems that are commercially available at this time are tripwire systems. Limitations of tripwire systems become obvious in the presence of shadows and changing light conditions. Another disadvantage is the limited flow information that the systems provide—counts and speeds (other variables are calculated from these two variables). Tripwire systems are currently used to provide inputs to traffic control devices (*21*).

Closed loop tracking systems, the second generation of video image detection systems, are an extension of the tripwire approach in that detection is performed using the same type of detection zones. These systems have the same limitations found in tripwire systems with obscurations and shadows. Closed loop tracking systems are the first attempt to perform vehicle tracking. Closed loop systems provide more traffic flow information than tripwire systems, but the complexity of both hardware and software subsystems is significantly greater than for tripwire systems (*21*).

Data association tracking systems, commonly used in satellite surveillance systems, are the third generation of video image detection systems. A basic requirement of data association tracking is the capability to identify and track a distinguishable object as it passes through the field of view of the camera. In this mode, the computer identifies vehicles by searching for connected areas of pixels that indicate motion when compared with the background information. A series of such vehicle detections is then associated to produce tracking data for each vehicle.

This approach requires less processing power and speed than closed loop tracking because it does not have to operate at the frame rate of the camera. It offers good performance with shadows and obscurations. Shadows are addressed using image analysis. Observed differences in the geometry of the image reduce the effects of obscuration. A greater reliance on software sophistication may reduce the hardware costs for these systems. Data association tracking systems have the additional advantage that a series of video cameras can be used to cover a wide area, and a vehicle can be handed off from one sensor to another as it passes from one field of view to another.

2.4 FIELD PERFORMANCE TESTS

2.4.1 California Polytechnic State University Field Performance Tests

MacCarley et al. reported on results of testing 10 commercial or prototype video image detection systems available in the United States (*22*). The California Polytechnic State University researchers evaluated eight of the 10 systems in field performance tests. The systems evaluated in field performance tests were: Aspex Traffic Analysis System (ATAS); the Camera and Computer Aided Traffic Sensor (CCATS) by Devlonics in Belgium; Sigru, developed by Eliop in Spain; the Traffic Analysis System (TAS); Titan, a French system under development by the Institute National de Recherche sur les Transports el leur Securite, INRETS; Traffic Tracker; Tulip; and Autosome.

All of the systems available for this test by Cal Poly were software-based. Some systems required specialized hardware platforms, while others ran on IBM PC-compatible platforms requiring only video digitizing cards for the camera interface. A fundamental part of the software's task involved algorithms for detecting the vehicle and measuring its speed (*23*, *24*, *25*, *26*, *27*). For the systems tested, two fundamental types of algorithms, Type 1 and Type 2 were examined.

Type 1 algorithms detect the time difference of light-level changes between two virtual gates in the image that are spaced a known physical distance apart. As a vehicle moves through the detection zone, it causes a difference in intensity, initially at the first gate, then at the second. This sequence of events is determined to be a single vehicle, and the vehicle velocity is determined by the time difference between the two events.

Type 2 algorithms, also known as vehicle tracking algorithms, first detect the presence of a cohesive object moving in the detection zone and then measure the vehicle's velocity along its trajectory. These algorithms are generally more sophisticated and typically require significantly greater computer processing power.

The test team used 28 test conditions in an attempt to emulate actual field conditions encountered on California urban freeways during year-round service. Parameters included day and night illumination levels, variable numbers of lanes (two to six), camera height, camera horizontal angle with the roadway, inclement weather conditions (rain and fog), camera sway and vibration, differing levels of traffic congestion, shadows, and the effects of simulated ignition noise and 60 Hz electromagnetic noise. Researchers developed a series of video test segments from several hundred hours of raw video collected over a period of a year on urban freeways. Each actual test segment was 20 minutes in length, preceded by a 10-minute initialization period to allow the test system to cancel the background and adjust to ambient light conditions. Video images came from cameras mounted on freeway overpasses at heights varying from 8.3 m to 14.2 m above the roadway surface with a lens system that permitted viewing all traffic lanes in one direction.

Evaluation results indicated that most systems generate vehicle count and speed errors of less than 20 percent over a mix of low, moderate, and high traffic densities under ideal conditions (*22*). Parameters that may reduce the accuracy of a system are discussed below. Systems designed for very high camera placement were often intolerant of partial occlusion of vehicles (partially or fully hidden from view), yielding high error rates with lower camera mounting heights. Tests of high-density, slow-moving traffic yielded reduced accuracy and sometimes complete detection failure.

Transitional light conditions during sunrise and sunset also led to a reduction in accuracy. This was of significant concern because these time periods may occur during the heaviest traffic flow. Video image detection systems equipment is undergoing transition from daylight algorithms, which detect entire vehicles, to nighttime algorithms, which detect headlight pairs during these time periods. Finally, two aberrant conditions that caused particularly high error rates for most systems were rain at night and long vehicular and stationary shadows.

2.4.2 Minnesota Guidestar Field Performance Tests

The Minnesota DOT and SRF Consulting recently finished conducting a two-year test of non-intrusive traffic detection technologies under the auspices of Minnesota Guidestar. This test, initiated by the FHWA, had a main goal of providing useful evaluation on non-intrusive detection technologies under a variety of conditions. The researchers tested 17 devices representing eight different technologies: passive infrared, active infrared, magnetic, radar, Doppler microwave, pulse ultrasonic, passive acoustic, and video. The technologies were tested at a site in Minnesota that provided a wide range of weather, lighting, traffic and geometric conditions. Two locations were selected for testing, the first location was a freeway site, and the second site was an intersection. Inductive loops were used for baseline calibration. The test consisted of two phases, with Phase 1 running from November 1995 to January 1996 and Phase 2 running from February 1996 to January 1997 (*28*, *29*, *30*). Table 2-1 summarizes the most pertinent detectors.

Because of the number of technologies tested and the variety of conditions under which the technologies were tested, the results and conclusions of the research were varied and complex. Researchers found that it is important to consider the detection device's intended application when evaluating performance (*30*). The performance results for each of the eight technologies tested in the Minnesota Guidestar testing are discussed below.

2.4.2.1 Passive Infrared Devices

Passive infrared devices use the measurement of infrared energy radiating from a detection zone to detect the presence of vehicles. Researchers found that passive infrared technology performed well at both freeway and intersection testing locations and is a good technology for monitoring traffic in urban areas. The passive infrared devices tested during the Guidestar test were the Eltec Models 833 and 842, and the ASIM IR 224. The researchers found that passive infrared devices were not impacted by weather conditions and were very easy to mount, aim, and calibrate. However, there were significant differences in performances of the devices tested (*30*).

The Eltec Models 833 and 842 are self-contained passive infrared detectors that are easy to mount and calibrate. The Eltec models, which are designed to be mounted either overhead or slightly to the side of the roadway, can be used facing either oncoming or departing traffic. However, repeatability was an issue and in some instances had significant fluctuations in count accuracy. The best performance occurred during a 24-hour test when the device counted within 1 percent of baseline data (*30*).

The ASIM IR 224, which is designed to be mounted either overhead or slightly to the side of the roadway, must face oncoming traffic. This passive infrared detector monitors three measurement zones and a vehicle must pass through all three zones in order to be counted as a detection. The IR 224 was easy to mount and calibrate, and repeatability was good. One device was observed to undercount vehicles during snowfall, however this miscounting may have been the result of vehicles traveling outside of the sensor's detection zone. The results of this device

Table 2-1. Summary of Non-Intrusive Sensors [a]

TECHNOLOGY	VENDOR/PRODUCT	STATED CAPABILITIES	APPROX. COST	ADDITIONAL EQUIPMENT
Active Infrared	Schwartz Electro Optics, Inc. Autosense I	volume, occ., density, speed, class, presence	$6,500	PC, mounting bracket
Passive Infrared	ASIM Engineering Ltd. (Switzerland) IR 224	volume, occ., presence	$1,400	PC with interface box and display software (optional)
Passive Magnetic	3M Microloop	volume, occ., presence, speed (with 2 sensors)	$500 - $800 (b)	
Passive Magnetic	Nu-Metrics NC-40, NC-90A G-1, G-2 (wireless)	NC-40: vol., occ., presence NC-90A: same + spd, class, length G-1: vol., occ., presence, temp. G-2: same plus speed, class, length	NC-40: $550 NC90A: $895 G-1: $975 G-2: $1,695	PC, computer interface ($450), software ($745) & protective cover ($158 NCs only)
Radar	EIS, Inc. RTMS X1	volume, occ., speed, presence, turning movements, class.	$3,500	PC for setup and for serial data
Doppler Microwave	Microwave Sensors, Inc. TC-20/TC26B	volume, occ., (20 is short range, 26B is long range)	TC-20: $630 TC-26B:$375	
Doppler Microwave	Whelen Engineering TDW 10/TDN 30	volume, occ., speed (TDW is wide bm), (TDN is narrow bm)	$995	PC for serial data (optional)
Passive Acoustic	AT&T/IRD SmartSonic TSS-1	volume, occupancy, speed	$1,450	Mounting brackets, PC for serial data - opt.
Video Tracking	ELIOP Trafico S.A. (Spain) Eva 2000 S	volume, occ., density, presence, speed, class, headway, (price varies w/ features)	$7,000 - $17,000	386 PC, camera, software
Video Tripline	Econolite Autosome 2004	volume, occ., density, presence, speed, class, headway, turning movements	$17,000 (1 camera unit) $24,000 (4 camera unit)	486 PC (cameras included)
Video Tracking	Peek Transyt VideoTrak 900	volume, occ., density, presence, speed, class, headway, turning movements, incident detection	$18,000 (4 camera unit)	486 PC, cameras
Video Tripline	Rockwell International TraffiCam	volume, occ., speed, presence	$3,800	386 PC (camera included)

[a] Source: Reference *(30)*

[b] Price is estimated.

during an optimal 24-hour count period at both the freeway location (within 1 percent of baseline data) and the intersection (within 2 percent of baseline data) were among the best results obtained (*30*).

2.4.2.2 Active Infrared Devices

An active infrared device detects vehicle presence by emitting laser beams at the road surface and measuring the time it takes for the reflected signal to return. If a vehicle is present, the return time for the reflected signal will be reduced. The Schwartz Autosense I was the only active infrared device tested and it was not tested at the intersection location. In addition to detecting stationary and moving vehicles by presence, the Autosense I system can obtain vehicle speed and vehicle profile (which can be used for classification). One drawback noted was that incoming data are not clearly time stamped (*30*).

Autosense I was found to be very accurate at counting traffic at the freeway location; however, weather conditions did impact performance of the device. The research team observed that during periods of heavy snowfall, the detector both overcounted and undercounted vehicles. The undercounting was surmised to be the result of vehicles traveling out of the detection zone. The overcounting was attributed to the falling snow reflecting the laser beams causing false detections. Researchers also observed that rain and freezing rain caused overcounting and undercounting. These discrepancies were attributed to the change in reflectivity properties of the pavement (*30*).

2.4.2.3 Passive Magnetic Devices

Passive magnetic devices detect the disruption of the earth's magnetic field caused by the movement of vehicles. The passive magnetic device must be relatively close to the vehicles it is detecting, therefore most applications of this type of device require installation below the pavement or in a sidefire mode. Two magnetic devices were tested during Guidestar, the Safetran IVHS Sensor 212E and 232E Probes. Two Safetran 231E Probes were installed in conduits underneath the roadway and were connected to the IVHS Sensor 232E, a processing card located in a collection trailer. Volume, speed, and occupancy can be calculated from the detector data. The data from the probes, which were located approximately 6 m (20 ft) apart, could also be used to calculate speed. Installation of the passive magnetic devices was difficult and required several days. Water was also observed to accumulate in the conduit and at the handhold area of the conduit, which possibly resulted in problems with the probe's performance (*30*).

The probes had problems with erratic performance which could be due to intermittent grounding problems. The problems were observed during periods of rainfall. Snow and rain also affected detector performance. Overcounting during periods of snow was attributed to vehicles leaving the detection zone. Problems with rain was surmised to be due to water entering the conduit handhold and shorting out the probe connections at the splice (*30*).

2.4.2.4 Doppler Microwave Devices

Doppler microwave devices transmit a beam of low energy microwave radiation at a target area on the pavement and then analyzes the reflected signal. The motion of a vehicle in the target area or detection zone results in a shift of frequency of the reflected signal according to the Doppler principle. This shift can be used to detect moving vehicles and estimate their speed. Four different Doppler microwave devices were tested, but the research team presented detailed data for only two of the devices. The devices tested were the Peek PODD, the Whelen TDN-30, the Whelen TDW-10, and the Microwave Systems TC-26B. The research team found that all four devices were easily mounted and calibrated, and that none of the devices seemed to be affected by weather conditions. However, the devices tested revealed differences in performance. The study did not provide data for either the Whelen TDW-10 or the Microwave Systems TC-26B (*30*).

Researchers found that under optimal conditions the Peek PODD was able to count vehicles at the freeway site within 1 percent of the baseline, providing that the device was properly aimed. The PODD requires that mounting be either overhead or slightly to the side of and facing oncoming traffic. These mounting requirements resulted in poor aiming of the device which may have led to undercounting during one test and overcounting during another. During one of the procedures it was observed to detect vehicles in the adjacent lane. The PODD was not able to collect good data for the intersection site. The Whelen TDN-30 also requires that mounting of the device be either overhead or slightly to the side of and facing oncoming traffic. The primary role of the device is to collect speed data. Researchers found that the device undercounted vehicles at the freeway site by approximately 3 percent and was not able to collect meaningful data at the intersection site (*30*).

2.4.2.5 Radar Devices

Researchers tested one radar device during the test. Radar devices use a pulsed signal that is either frequency-modulated or phase-modulated. The device determines the delay of the return signal and uses this information to detect the presence of a vehicle and to calculate the distance to the detected vehicle. The radar device tested by researchers was the EIS RTMS. This device can be mounted either overhead or in a sidefire position and can be aimed perpendicular to traffic. The RTMS was easily mounted but requires a moderate amount of calibration to achieve optimal performance. The researchers found that rain affected the performance of the RTMS. This degradation in performance was attributed to water entering the device and not to limitations of the technology. When the RTMS was used in an overhead mounted position the device undercounted vehicles by 2 percent or less at the freeway site. When the RTMS was in a sidefire position, the device undercounted by approximately 5 percent. The RTMS was not tested at the intersection site (*30*).

2.4.2.6 Passive Acoustic Devices

Passive acoustic devices incorporate an array of microphones aimed at the traffic stream; a vehicle is counted when the microphones detect the sound of the vehicle passing through the detection area. The optimum position for passive acoustic devices is the sidefire mounting position with microphones aimed at the tire track because the primary source of sounds for vehicle detection is the noise generated between the tire and road surface. Researchers tested two passive acoustic devices that were supplied by the same manufacturer, the IRD SmartSonic. The devices were mounted sidefire and were noted to be relatively easy to install and calibrate. Low temperatures and the presence of snow on the roadway, which may have muffled sound, were both correlated with undercounting by the devices. When the SmartSonic devices were mounted on the freeway bridge undercounting daily traffic ranged from 0.7 to 26.0 percent. This undercounting was attributed in part to the echo-filled environment underneath the bridge. Researchers found that both SmartSonic devices undercounted vehicles during freeway testing and overcounted at intersection testing (*30*).

2.4.2.7 Pulse Ultrasonic Devices

The research team tested two pulse ultrasonic devices, the Microwave Sensors TC-30 and the Novax Lane King. A pulse ultrasonic detection device emits pulses of ultrasonic sound energy toward a detection zone and then measures the time it takes for the reflected pulses to return. If a pulse is returned sooner than expected the presence of a vehicle is detected. Overhead mounting of the device provides optimal signal return and vehicle detection, however sidefire mounting is possible for some devices. Pulse ultrasonic devices are relatively easy to mount, however the ease of calibration varies with devices. Weather conditions did not impact the performance of the devices (*30*).

The TC-30, which may be mounted either overhead or sidefire, was found to provide an accurate vehicle detection count at the freeway test site and a tendency to overcount at the intersection test site. The TC-30 was easy to mount and calibrate. Researchers observed that vehicles stopped in the detection area were counted multiple times resulting in the overcount. The Novax Lane King can also be mounted either overhead or in a sidefire configuration. The Lane King was easy to mount, however calibration was extensive for optimum performance. The Lane King was extremely accurate in counting vehicles at the freeway site, but at the intersection site overcounting occurred as the result of double counting. The two pulse ultrasonic devices interfered with one another when mounted next to each other (*30*).

2.4.2.8 Video Devices

Video detection devices analyze video images from a camera by using a microprocessor. Researchers tested four video systems, the Peek Transyt VideoTrak-900, the Image Sensing Systems Autosome 2004, the Eliop Trafico EVA 2000, and the Rockwell International TraffiCam--S. In general, mounting video detection devices is a more complex procedure than that required for other types of devices. Camera placement is crucial to the success and optimal performance of the detection device. Lighting variations were the most significant weather-related condition that impacted the video devices. Vehicle shadows, other shadows, and transitions between day and night also impact counting (*30*).

The Peek Transyt VideoTrak-900 is capable of monitoring input from up to four cameras. Initial testing by the research team at the freeway test site resulted in counting accuracy within 5 percent of the baseline. However, when the device was moved to the intersection, periodic failures began to occur and continued throughout the testing. Researchers also observed that overcounting occurred during the light transition periods from day to night and vice versa. Like the VideoTrak-900, the Autosome 2004 can also monitor input from up to four cameras. Researchers found that the Autosome is capable of performing within a 5 percent accuracy at both freeway and intersection test sites. Light changes during transition periods also resulted in undercounting by the Autosome (*30*).

Researchers found that the Eliop Trafico EVA 2000 detection system was capable of very accurate freeway counts, within 1 percent of the baseline. Calibration of this system was difficult as a result of a complicated user interface; however, the system was not adversely impacted by any weather condition and was the only video system that was not affected by light transitions. The EVA 2000 was not recommended for intersection applications and therefore the researchers did not supply any data for intersection testing. The last video device tested by the researchers was the Rockwell International TraffiCam--S. The TraffiCam required data to be downloaded over the serial connection. Researchers found that the TraffiCam's performance varied greatly during the testing period. Some of the performance problems were attributed to a grime buildup due to salt spray on the camera lens. Other variables that may have affected the performance were shadows and lighting conditions (*30*).

2.4.3 Hughes Aircraft Company Field Performance Tests

Hughes Aircraft Company conducted an extensive test of non-intrusive sensors for FHWA. The objectives of the study, *Detection Technology for IVHS* (*31*), included determining traffic parameters and accuracy specifications, performing laboratory and field tests of non-intrusive detector technologies, and determining the needs and feasibility of establishing permanent vehicle detector test facilities. Detector technologies that were tested included: ultrasonic, Doppler microwave, true presence microwave, passive infrared, active infrared, visible VIDS, infrared VIDS, acoustic array, SPVD magnetometer, and inductive loops (*31*).

The field tests were conducted on both freeway and surface street test sites. Sites selected were located in Minneapolis, Minnesota; Orlando, Florida; and Tucson, Arizona. These sites were selected to allow testing to be conducted in a variety of climatic and environmental conditions. Researchers made both quantitative and qualitative observations and judgments regarding the best performance with respect to different traffic parameters. The Doppler microwave detectors provided the best performance for gathering specific data for most categories, however it should be noted that this detection technology does not detect stopped vehicles. Researchers found that the Doppler microwave, true presence microwave, visible VIDS, SPVD magnetometer, and inductive loop technologies performed well for low volume counts. The Doppler microwave, true presence microwave, visible VIDS, and inductive loop performed well for high volume counts. The Doppler microwave was the best performing technology for low volume speed and for high volume speed. The Doppler microwave, microwave true presence, SPVD magnetometer, and inductive loop technologies performed best in inclement weather.

2.4.4 Other Field Performance Tests

Recent tests by Kyte et al. (*32*) substantiated that less accurate (uninterrupted flow) measurements from an Autosome 2002 video imaging system occurred under reduced daytime light conditions, when traffic moved toward the camera (versus away), and when vertical detectors were used. In the measurement of freeway traffic volume counts using proper camera angle and detector configurations, these Autosome tests produced data that varied from 0.6 to 9.3 percent of manually collected data.

Duckworth et al. (*33*) conducted tests of various traffic monitoring sensors on a highway near Boston. Sensors tested included: video cameras, passive acoustic microphone arrays, active ultrasonic acoustic ranging and Doppler sensors, Doppler radar, and passive infrared sensors. The researchers evaluated and considered the sensor performance, sensor cost, communications required raw data, and the amount of computation needed for signal processing and classification. The researchers found that the video camera provided the best performance in the areas of detection, speed estimation, and vehicle classification. However, they noted that video had limitations in poor lighting and certain weather conditions, and was the most expensive sensor tested. Pulsed ultrasound was found to be the best sensor for detection and classification when cost, the communications bandwidth requirements, and processing power were considered. Radar was the best velocity sensor for vehicles it detected. The researchers recommended that a combination sensor of pulsed ultrasound and either pulsed-Doppler ultrasound or Doppler radar be considered as the strongest candidate as an inexpensive replacement of magnetic loop detectors (*33*).

3.0 SURVEY OF DETECTOR USAGE

3.1 INTRODUCTION

TTI conducted a telephone survey of all the TxDOT districts as well as out-of-state jurisdictions that have tested and/or implemented non-intrusive detectors. This began with researchers submitting to TxDOT Research and Technology Transfer (RTT) the survey form for approval. Once approved, TTI began making phone calls to in-state and out-of-state agencies to gather information. The Appendix shows the survey used for gathering this information.

3.2 TXDOT DISTRICTS

3.2.1 Abilene District

The only detector type used by the Abilene District is inductive loop detectors (ILD); approximately half of their 30 isolated intersections are actuated. Therefore, assuming an average of 457 linear meters (1,500 linear ft) of loops per intersection, the district maintains approximately 13,720 linear meters (45,000 linear ft) of ILDs. The detections are only used for signal control —pulse or presence. The district does not use the detectors for vehicular counts; although the spokesperson mentioned that Traffic Planning and Programming in Austin has automatic vehicle count stations in the district. The only additional data the district might collect is traffic counts at intersections to maintain the appropriate signal timing.

The Abilene District believes their loops are accurate and dependable over 90 percent of the time. The accuracy has been verified by technicians doing periodic checks in the field. Also, technicians respond to calls from motorists who observe problems at traffic signals. The district does not contract any of this ILD installation and maintenance work. The limited problems encountered by the district with ILDs are related to high plasticity clay soils that allow the pavement to "shove" in the vicinity of stop bars. All their loops are in asphalt. The district experiences problems with loops approximately four times each year.

There are no technologies of vehicle sensors that the district has used but rejected. VIDS is currently under consideration as a solution to pavement problems. However, the district has not initiated procurement. The district did not have cost information available.

3.2.2 Amarillo District

Neither of the two district personnel interviewed (one from the Traffic Engineer's office and one from the Signal Shop) wanted to estimate the number of inductive loops installed in the district. The ILDs are primarily used for intersection control. Currently, the district has only considered using other detection technologies besides inductive loops, but they have not purchased any others.

The type of information gathered from the ILDs is only that used for each individual intersection. There is one closed loop system (I assume downtown) that offers the capability of storing traffic count information; however, it is not currently used for that purpose. The district also has a few SHRP sites where classification counts are conducted periodically, although neither person knew much about them.

The spokesman from the Traffic Engineer's office indicated only one problem with ILD accuracy and, that had to do with detection of motorcycles when the motorcycle was the only vehicle over the ILD. The district has compensated in some cases by increasing the loop detector sensitivity. However, if increased too much, this can create another problem -- cross-talk between adjacent loops. The district has not experienced weather-related problems with ILDs. During the past three years, the spokesman knew of no testing of non-intrusive devices, although he saw a demonstration of the Rockwell TraffiCam in Austin and has read about VIDS such as Autoscope. The following statement may have been a reiteration of something he heard from Rockwell: "Loops wear out in approximately two to three years, but the Rockwell device can last 20 years." He stated that their Traffic Operations Division in Austin typically conducts preliminary tests and forwards results to the districts.

The spokesman from the signal shop stated that he is interested in finding a good replacement for inductive loops, but he has heard negative feedback from districts that have tested new devices. For the annual cost of ILDs for this district, the past few years' costs have remained fairly stable at approximately $100,000. However, this annual cost is anticipated to decline since they are now "caught up" on their backlog of defective sensors. At any given time, the district experiences problems with 15 to 20 percent of loops. The district's last year's loop contract was unavailable (for specifics). Their loop costs are based on the unit of linear feet of loop, rather than on nominal dimensions of the loop (e.g., 1.8 m by 1.8 m (6 ft by 6 ft)). Otherwise, to break it down into other specifics, we would have to discuss duct wire vs. plain wire, encapsulated vs. non-encapsulated, and so forth.

The district is interested in anything that is better than loops. One vendor, Naztech, recently approached district personnel to sell their microwave detector. Another district had reported acceptable performance at a signalized intersection, so the Amarillo District is considering it now. One of their present needs is in the small town of Canadian, Texas, where they cannot bore under the road at this location due to close proximity to buildings.

3.2.3 Atlanta District

The Atlanta District transportation operations engineer provided the following information regarding the district's 64 intersections that utilize loop detection. The engineer stated that at an average intersection there are approximately 460 m (1,500 linear feet) of loops. Based on this figure, they have approximately 29.3 km (96,000 linear feet) of loops. During the last fiscal year the district replaced 1,220 m (4,000 ft) of these loops at an average cost of $10.66 per m ($3.25

per ft). Total annual cost was approximately $13,000.00 (4 percent failure rate when combined with maintenance and milling operations).

The Atlanta District currently uses inductive loop detectors throughout with the exception of three intersections which use the "Accuwave" detector marketed by Naztech. The district spokesman stated that he would like to find an alternative to loops but from what he has heard and read, other technologies are not as accurate as loops. When loops need maintenance the district signal shop utilizes their loop contract by contacting the contractor to get the needed maintenance done. The installations done by this district are strictly saw cuts, using 3M Loop Sealant to fill the saw cuts. They do not use encapsulated loop wire products. The district provides traffic control for the contractor when installation and maintenance are needed. The engineer estimated that between 10 and 20 percent of ILDs fail at any given time. However, this is a "mixed" number because they might replace one loop multiple times in a year whereas others might last 10 years without any maintenance.

The "Accuwave" detector is the only non-intrusive detector that the district has installed thus far. It utilizes one detector on the signal pole (not on the mast arm) for each approach of up to three lanes. The district installed power and communications using copper wire connection between the sensor and the controller cabinet. The district will install these or similar devices only on low volume approaches. As far as features it offers, the Accuwave system allows the user to input a delay value, such as for right turning traffic. The spokesman has only heard limited negative motorist feedback, so he believes the detectors are functioning fairly well. Adjusting the delay may resolve these problems. A minor initial problem was tree limbs within the detection area causing false detections as they moved with the wind. Once the limbs were cleared, the problem no longer existed. Other desirable parameters that need to be measured are vehicle counts and turning movements. The Atlanta District is also anticipating installation of VIDS at two intersections, with consideration being given to only two suppliers: Peek and Autoscope.

3.2.4 Austin District

The Austin District currently has approximately 600 intersections with inductive loops for signal control. District personnel estimate that, on the average, there are 16 ILDs per intersection and a total number of loops at approximately 9,600. The district also has three microwave sensors, one "Sound King" passive acoustic by Novax of Canada, and 14 Odetics VIDS units. Austin was initially involved in the Beta testing of Odetics before it actually went "on-line" to control any traffic signals. These detectors are being used primarily for intersection signal control, especially near railroad tracks, and also for non-signalized applications such as construction zones.

Limitations of microwave and acoustic detectors are that they lock the detection (do not offer delay feature). So, on right-turn lanes, the vehicle may make a free right turn and there is no demand to be serviced for the approach when the signal actually turns green. Therefore, the district has received several complaints about these two detectors. There are also weather-related problems such as fog or rain that resulted in diminished performance. For the acoustic, the detection zone on the pavement is very small -- approximately 0.76 m (2.5 ft) in diameter. This presents problems when the detector is mounted in the sidefire mode, although it does not seem to pose a problem in an overhead configuration. The microwave sensor's detection area is much larger, at approximately 5.5 m (18 ft) on the longest side. All detectors are typically used for presence, although the Odetics can utilize presence or pulse.

The district only had approximate life and cost information on ILDs, partly because they have not used loop contracts. However, they are preparing to implement a loop maintenance contract in the immediate future. A loop lasts on average approximately three to five years in Austin. Typical problems with ILDs include road deterioration that then causes loops to fail. Austin's contract will include everything exterior of the cabinet. The contract had been sent out at the time of this interview and bids received, so final negotiations were pending.

The newer Eagle controllers have the capability of utilizing the vehicle counts and recommend cycle lengths. The Austin District is beginning to consider the potential that is available with this information to optimize traffic flow and progression. The Austin District would also like to be able to conduct turning movement counts. Sometimes, they place road tubes on the downstream side of the intersection to determine what the demand is to achieve adequate progression for the next downstream signal. Therefore, if the detector is able to count turning movements, the demand could be adjusted at the next signal. The district has not used the Odetics units for pedestrian detection except during short test periods.

The accuracy of the new Odetics system before it was placed on-line was a very important issue to TxDOT. The vendor collected and downloaded data and analyzed it to "fine tune" their video system so that it closely replicated the inductive loops that were still being used at the first intersection. After approximately six months of this fine tuning, intersection control was turned over to the Odetics system instead of the loops. This was only after the Traffic Operations Division, the district traffic engineer, and everyone else was comfortable with the system's reliability. The district initially had reflection and shadow problems with the Odetics system, but these were later resolved. Nighttime wet streets also initially caused problems but the reflected headlights were filtered out.

The only detection technology tried but rejected by the Austin District was Microloops. The district has 10 of them that they do not intend to use. The detectors use a proprietary amplifier that creates compatibility problems. A technology that the Austin District is evaluating for communicating among the various systems and from one intersection to another is Spread Spectrum. They recently bought 22 units for immediate implementation.

The Austin District has, for the most part, not documented costs of the various detection technologies, including ILDs. One exception is the cost of typical maintenance items at signalized diamond interchanges. The Austin District has an agreement with the city of Austin to pay for maintenance at these interchanges. The TxDOT spokesman calculated an annual maintenance cost for elements at the intersections (excluding the cabinet and large items like controllers) to be $1,500 to $1,600 per year per interchange. The city currently maintains 40 of these interchanges.

3.2.5 Beaumont District

The Beaumont District has 130 to 135 signalized intersections, although some are pretimed and do not have detectors on the approaches. The district currently has two TC-20 Microwave pulse sensors (radar technology) that are used on side streets to detect minor street traffic. The district is dissatisfied with these detectors because they are difficult to tune and are susceptible to other "noise" in the right-of-way. Moving branches within its field of view cause it to indicate a detection. The detection range of the TC-20 is approximately 30 m (100 ft). This same company makes another unit called a TC-26, which has a greater range of approximately 91 m (300 ft).

The district has also purchased approximately 28 to 30 Accuwave sensors from Naztech for installation in the immediate future. Their contractor was in the process of installing them in April 1997. District personnel have also seen some literature on a Swedish detector by the name of ***ASIM***, that uses passive infrared with active infrared to get presence detection. They like what they know about it, but have not purchased any yet.

The Beaumont District spokesman stated that their traffic section does the traffic counts, often relying on manual counting procedures. However, they need a system that could automate this process. The Accuwave sensors are programmable using a laptop and the appropriate software, and they allow adjustment of detection boundaries. These detectors appear to be very stable, although the manufacturer admits they generate false detections in rain.

Accuracy of ILDs is satisfactory, although the district has not formally tested them. Microwave detectors typically do not miss many vehicles, depending upon intersection geometrics. Sometimes vehicles stop beyond the stop bar and the detector misses them. This district uses 1.5 m by 1.5 m (5 ft by 5 ft) diamond shaped loops -- usually two or sometimes three in the left-turn lane and two on the cross street approaches. They also use one on the main lanes farther back from the stop bar for pulse. These diamond-shaped loops detect motorcycles without requiring increased sensitivity, partly as a result of improvements in detector amplifiers over the past few years.

This district spokesman did not know of other information that should be collected with existing or new detectors. The district is forced to operate in a reactive mode and evaluate general trends or patterns that indicate a particular problem. If a detector is operating without obvious malfunctions and no complaints are raised, the district does nothing to alter the detector.

Problems encountered with the ILD are sometimes a function of pavement condition, especially at the stop bar. Sometimes asphalt pavement "shoves" at the stop bar and causes loop failures. To alleviate this problem, a small amount of cement is added to the hot mix to make the asphalt stiffer. In one case, the district had to undercut the pavement and subgrade for approximately 7.6 m (25 ft) back of the stop bar, then overlay with new material. In some installations in concrete, the district uses a foam rod 25 mm (1 in) deep and fills over that with flexible sealer like the 3M loop sealant. This gives loop wires more flexibility and reduces stress on the wires. However, this is not used in asphalt; it would eventually push the wires to the surface. Solid encapsulation is better in asphalt.

As for other technologies tested, the district experimented with an acoustic detector in the early 1970s. Results were disappointing. The spokesman expressed that they have had their share of problems with inductive loops prior to the time they were improved. When there was no fail safe mechanism, there would be a constant call to the cabinet. Installing newer cabinets have helped alleviate this problem. The spokesman described the type of detector that would be most useful to them as one that would mount on a signal pole and detect vehicles approaching from several hundred feet back of the stop bar.

The district conducted a study on costs of ILDs and found that costs vary by location. They have had some that have been in the road for 10 years and are still working, while some of their loops in asphalt only last one year. The district uses special measures to try to solve problems as soon as they are detected or if they expect a problem to occur due to pavement conditions. If the loop wires cross an expansion joint in concrete, they leave extra slack in the wire. Sometimes, the wires still fail. Soil in the southern part of their district is a gumbo clay and very expansive, so slabs may move as much as 51 mm to 76 mm (2 in to 3 in).

The Beaumont District uses a loop contract for some loop repairs. Even though the district has the equipment to install and repair loops, a contractor can do the job more efficiently simply because they do it all the time. One of their problems is a shortage in contractors that install ILDs. At one time, the 1.5 m by 1.5 m (5 ft by 5 ft) loops cost $500, but their cost is slightly less today. The district's current contract cost for loops in asphalt is $12.30 per meter ($3.75 per linear foot) and $15.58 per meter ($4.75 per linear foot) in concrete. A complete typical intersection costs $3,000.

3.2.6 Brownwood District

The Brownwood District has a total of only 35 signalized intersections, all of which use inductive loop detectors and a few are semi-actuated. The district recently ordered microwave *presence* detectors, but they have not arrived. The district spokesman had seen a demonstration on a VIDS system, but the district had not installed any.

All of the data collected from ILDs is used for operating traffic signals; this group does not conduct traffic counts. The district chooses to do its own detector installation and maintenance. The signal shop learns of ILD problems two ways: they conduct routine maintenance twice a year, and they receive reports by motorists. The most common problem they have is not the loop, but the detector amplifier. As in other locations, the life of ILDs varies considerably, but this district typically replaces six per year, including those damaged by utility companies or milling operations. When the district continues to have problems at a particular location, they sometimes consider replacing loops with another technology. An example is at the intersection of U.S. 377 and F.M. 2524 where truck traffic is a significant portion of total traffic. The pavement had failed so ILDs were not the most appropriate choice.

To overcome the problem of pavement exerting excessive stress on ILD wire, the district designed a six-sided loop where all of the intersecting angles are flat enough that stresses are reduced. Another positive feature was increased sensitivity over that of a rectangular loop. The district is also now using PVC encapsulated loop wire because of increased sensitivity and reduced amount of wire needed. The opposite (parallel) sides are six feet apart. The district uses less loop sealant and crews can complete an installation in less time. They started by making a hinged sheet aluminum pattern to facilitate marking the layout. Other jurisdictions have experienced problems with lightning, but this district claims to have eliminated this problem by using bare copper connected to chassis ground. This eliminated lightning proximity hits, but direct hits are still a problem.

This district spokesman believes that they have good equipment and some of the best techniques for installing loops. They have a Target "65" pavement saw and they cut 5 mm (3/16 in) width cuts for loop cuts. They currently cut wet, but they will soon begin dry cutting due to the time required to dry the saw cuts.

Other information that will become more useful in the future is traffic count information. The signal shop anticipates installing some volume-occupancy timing plans in a few locations. The district spokesman is currently designing a new intersection incorporating extra loop leads to collect vehicle count data. The district also needs turning movement counts.

The Brownwood District has not tried anything other than ILDs; however, they are anxious to discover better technologies and methods. They generally depend on what General Services in Austin chooses to purchase, even though the spokesman does not always agree with their decisions. For example, he believes there is insufficient channel separation from card to card in the new cabinets. With adjacent loops on the same card, they experience cross-talk.

The Brownwood District has fewer signals than many other districts, and the district has only two people doing signal repair. The signal shop does not maintain cost records, and even if it did, there are difficulties in maintaining accurate costs. Assigning costs is based on certain function codes, which do not always distinguish specific activities. Therefore, going back in time to a certain work order when maintenance was done may not give all the necessary information. When these two signal persons travel to an intersection, they may be involved in several activities in that same trip to perhaps repair a controller. The traffic control costs would be salaries of county personnel plus the state employee salary costs and equipment costs.

3.2.7 Bryan District

The Bryan District has 83 signalized intersections, approximately half of which have inductive loops, primarily on left-turn lanes. Each intersection has approximately four loops per location (one for each left-turn lane), so the district estimates it maintains approximately 160 inductive loops. The only type of sensor other than ILDs that the Bryan District has installed is a TC-30 Microwave (radar) sensor. It lasted approximately six months before it failed. The district promptly removed the sensors and replaced them with ILDs. The only way the district utilizes its detectors is to control traffic signals. They would like to get traffic count information (vehicular volume) as well if their sensors and data storage capabilities allowed them to do so. The district is not interested in detecting densities or gaps. Problems encountered with ILDs stem from pavement problems, especially asphalt pavements that, near the stop bar, "shove" and stretch the loop wire. Table 3-1 is the district's most recent loop contract bid price dated December 12, 1996. Bid costs are based on linear measurement of loop installation. Boring is subsidiary to conduit and ground boxes are subsidiary to conduit. The district recently placed an order for a 150 "LX" microwave presence detector from Naztech. Its cost is $800 per detector plus another $100 for the board that goes inside the cabinet. Each card or board will accommodate two detectors.

3.2.8 Childress District

The Childress District currently has 60 inductive loop detectors that are only used for detection at traffic signals. District personnel believe that the ILDs are 97 percent accurate in terms of sending a "call" to the controller cabinet when a vehicle crosses them. Most are sensitive enough to detect motorcycles. The accuracy rate has only been verified by observation and not by a scientific method of data collection and evaluation. None of the detectors serve other purposes than signal operation. The district spokesman did not know of other information that the district would like to collect if they had the opportunity.

The district's only problem, noted by the spokesman in their experience with inductive loops, was loop wire being "pinched" by pavement shifts. The district has a substantial amount of truck traffic that contributes to asphalt pavements "shoving" in the vicinity of stop bars. Problems with inductive loops occur periodically, and the district typically makes the repair as soon as they have resources available. In the past, the district conducted their own loop installation and maintenance, but they are preparing to use a contractor for this activity. The cost of the loop contract, even though it is currently under consideration, was not expected to be available for some time, although their deadline for completing the bid process was September 1, 1997.

There are no detection technologies being considering for possible future use, and there are no technologies that have been tried and rejected. Some district personnel are considering the use of VIDS, but they want to wait until the technology is more mature. The district spokesman did not have cost information on inductive loop detectors.

Table 3-1. Bryan District ILD Contract

Item Description	Unit	Quantity	Unit Bid	Amount	Unit Eng. Est.	Over/Under	
						Dollars	%
Conduit (RM) (32 mm)	m	60	20	1,200	32.00	-720	-38
Conduit (PVC) (Schd 40)(50 mm)	m	1,100	15	16,500	12.75	2,475	18
Conduit (PVC) (Schd 80)(Bore)(50 mm)	m	100	40	4,000	50.00	-1,000	-20
Ground Box Ty A (122311) w/apron	ea	40	385	15,400	395.00	-400	-3
Traf Sig Cbl (Ty C) (2 Condr) (12 Awg)	m	1,200	5	6,000	2.00	3,600	150
Veh detector (14 Awg) (Blk)	m	4,000	15	60,000	14.00	4,000	7
Veh Detector (14 Awg)(Blk Tube)	m	60	15	900	21.00	-360	-29

3.2.9 Corpus Christi District

The Corpus Christi District maintains 168 signalized intersections, all of which have inductive loops. The number of loops per intersection varies from four to 20, and probably averages 12 per intersection. The district has 55 detectors that use microwave technology; 51 are Accuwave and four are TC-20 Microwave detectors. Some of the ILDs are used for speed and volume in the 16 closed loop systems that have recently come on-line. So far, there has been no formal study to evaluate the performance of these detectors, but the district knows some general facts about their operations. The TC-20 detectors perform acceptably, but the district is not as impressed with the Accuwave because of difficulties experienced in making adjustments to optimize performance. The district spokesman stated, "It has to be exactly right. Now, the district has 48 problems."

Data being generated from the closed loop systems includes not only control but also speed and count information. Because they have just come on-line, its operation has not been fully evaluated. The district spokesman could not think of other information that would be useful beyond what they are currently collecting. Inductive loops are prone to problems because they are located in the pavement. In one instance, a system of loops was being installed just before a rotomilling contract was let. Just as the loop installation was being completed, almost all of the ILDs had already been destroyed by the milling operation. The pavement is all asphalt in the Corpus Christi District and the soil is expansive clay, both factors that contribute to loop failures and a short useful life that only averages approximately one year in old pavement. In new pavement, useful life might be two to three years. The district lets a loop contract each year for replacements, utilizing their maintenance allocation for pavement improvements, then toward the end of each year deciding how much to spend for ILD repairs. The number of replacements depends upon the amount of money available.

The other technology in which the district is currently interested is VIDS. However, they want to approach this purchase much differently than they did on the microwave detectors and only make a small investment at first. District personnel realize that video detection is still developing. As of February 1997, the district was letting a project that includes two complete intersections.

The district spokesman said that his district is beginning to track costs associated with ILDs but results will not be available for approximately one year. District personnel know that loops costs may be more than competing technologies due to their high failure rate. By contrast, a district in west Texas where rainfall is much less and the soil support for pavement is much better, ILDs may be the most feasible detector type.

3.2.10 Dallas District

The Dallas District currently maintains traffic signals at 188 quad intersections and 32 diamond interchanges. This represents a total of approximately 4,720 inductive loops (assuming

20 per quad and 30 per diamond). The only other type of detector that the Dallas District has installed is pulse microwave, but the cities in the Dallas-Ft.Worth Metroplex maintain them now. The ILDs are only used to operate signals except in some cases they also store vehicle count data. Enabling vehicle counts requires a more expensive detector in the cabinet and different terminals in the cabinet, but the same loop could then be used for signal control and for counts.

The current contract for loop replacement is $12.30 per meter ($3.75 per linear foot) of saw cut, including saw cutting, placing wire, and sealing. The total cost is based on the loop cut length but also on the home run. For example, a 1.8 m by 1.8 m (6 ft by 6 ft) loop in the outside lane if 0.9 m (3 ft) off the curb would be paid on the basis of 8.2 m (27 ft), or $108.00. The second lane would be paid on the basis of 11.9 m (39 ft) of saw cut, or $156.00. On an annual basis, the Dallas District experiences an estimated 3 to 5 percent failure rate on inductive loops. The annual cost for loop repairs averages approximately $40,000. The district uses available maintenance money designated for loop repair until the fund runs low, then requests additional money.

Problems encountered with ILDs include failures due to poor pavement and cross-talk problems between adjacent detectors. Loops installed in poor pavement almost always result in a short life. One countermeasure to premature failures in the Dallas District is loop duct. It comes with the 14-gage loop wire encapsulated inside a 6 mm (1/4 in) polyethylene tube.

The only other technology installed for signal control in the Dallas District was microwave, although the freeway section is interested in TraffiCam by Rockwell. A spokesman involved in freeway operations emphasized that some jurisdictions seem to dwell on the more obvious parameters of vehicular speeds and counts, while ignoring other aspects that he referred to as how "component intensive" a system is. In other words, does a detection technology require the use of many components or a few? He is interested in the TraffiCam by Rockwell for the reason that it is simple to set up and operate even though it might not be as accurate as other, more expensive detectors. He likes the fact that the detector itself is very compact, and its power and communications lead is very small and self-contained. For freeway applications, he could install two units (one unit facing each direction of traffic flow) at half-mile spacings and have six detector stations feeding data and accessing power on the small cable supplied by Rockwell. This is very simple. It does not need the components required for ILDs such as cabinets, power drops, detector amps, extensive conduit, and so forth. Detection of failures is also very different with a unit like the TraffiCam. If one loop out of eight on an eight-lane freeway goes out, do you replace it or wait until more fail? With TraffiCam, the user would simply replace the detector and return the defective one for repair.

3.2.11 El Paso District

The El Paso District currently has 978 inductive loops spaced throughout the urbanized portion of the district. These are predominantly 1.8 m by 1.8 m (6 ft by 6 ft) square Type I loops that use five turns of wire in each loop. The primary use of these detectors is for operating traffic signals. However, the district also has a site at IH-10 and U.S. 54 where counts and speed information are collected and stored. They have experienced communication failures in getting detection information back to their offices. The district is not testing any newer technologies.

The district has experienced loop failures that required re-cutting the loops. As far as accuracy of the information the loops provide, the district has not formally documented their accuracy. They believe the loop sets are acceptably accurate for counts and speed detection. They spend time observing the detection lights inside the cabinet at signalized intersections, so they are pretty confident that the detectors work reasonably well. The most common problem with loops is rotomilling operations that destroy loops as they grind the pavement. The district does not currently use a loop contract for either replacement of failed loops or installation of new loops.

There are no technologies of vehicle detectors that the district tried and rejected. There are also none that they are currently considering. However, they might choose VIDS on freeways or in areas where cutting loops would not be feasible.

3.2.12 Ft. Worth District

The Ft. Worth District has approximately 2,000 inductive loops on freeways for surveillance purposes. This district has done considerable testing of non-intrusive devices over the past several months, and it is seeking an acceptable replacement for inductive loops. The district experiences problems with as many as half of their ILDs but the last time it repaired loops was four years ago. It does not want to interrupt traffic and risk the lives of their personnel to repair loops when non-intrusive technologies might come on the market to compete with loops.

The district tested the Electronic Integrated Systems radar detector, but its software was very difficult to use. The test location had retaining walls that apparently caused the radar beams to bounce from one surface to another and compromise the radar's accuracy. The district also tested two International Road Dynamics (IRD) SmartSonic units for six months. The units experienced occlusion because of the way they were mounted. The district connected them to a Local Control Unit (LCU), and mounted the two detectors over a four-lane roadway where the alignment was not very good. However, the SmartSonic detectors generated a consistent ratio of counts compared to loop counts, even though they were higher than the inductive loop counts at the same location. The district likes the ease of setup offered by these detectors; the company provides a video that quite adequately handles the setup process in a step-by-step fashion. The district purchased four of the IRD units, but they had not permanently installed them at the time of the interview.

The district had just finished testing the Peek VideoTrak™ 900 on April 8, 1997. The set-up was on a freeway where ILDs were available to provide comparable counts and speeds. Both ILDs and Peek fed data into a LCU for subsequent comparison. Comparing accuracy, there was a 15-minute interval during the daytime on the outside lane in which the Peek differed on a count of over 200 vehicles by only three vehicles. Moving from the outside lane to interior lanes (camera mounted at outside edge of freeway) there was more occlusion, and therefore more error. Accounting for this occlusion, the count accuracy was within plus-or-minus 5 percent on the next two lanes (again daylight) with traffic moving toward the camera. Results were inconclusive on the third lane. Desired accuracy depended heavily upon spending much time in setup. The count was in error by approximately 15 percent prior to the "fine tuning." The district has been unsuccessful in getting a factory representative to come to a field site and help with the setup. One of the problems associated with sending data is compatibility of the Peek with the Ft. Worth fiber-optic network. In bench tests, the Peek seemed to work acceptably but after field setup, it lacked the ability to accomplish "hand-shaking" so there were compatibility problems with communication protocols.

The district had previously tested a Westinghouse detector that combined sonar and radar technologies. The district personnel were very pleased with both its count accuracy and the ease with which it could be installed. It also provided both contact closure and serial output. One problem experienced was at their "canyon" (retaining walls both sides) where there was a rise in the roadway that occurred at the point where the radar determined speeds. They believe this rise compromised speed accuracy. The only reason the district did not purchase these detectors was that, soon after the test, Westinghouse sold this division.

The district tested Autoscope in the "canyon" approximately three years ago. At that time, the Autoscope detector had problems with the shadows cast during certain times of the day. There was bright sunshine during part of the day, but shadows were more extreme than perhaps other test locations. The district recorded a video at the site that has since become a test video used by Autoscope.

The only other non-intrusive technologies tested by the Ft. Worth District were the "Ground Hog" and a product by ShadCo. The district would be interested in testing the newer version of the Ground Hog. There were problems with ShadCo due to company personnel not being sufficiently familiar with the detector to set it up properly.

Information gathered from ILDs includes: occupancy, speeds, counts, and density (calculated from other parameters). Within the last three months (January through March 1997), the district developed the capability of data storage, but the full potential had not been realized. The district planned to store several years of data for each site. The TxDOT Traffic Operations Division recently provided software to the districts to allow for setting thresholds at monitoring stations for incident detection purposes. The software generates alarms when thresholds are violated. The Ft. Worth District, as of April 1997, had not finished installation and implementation of the software for use with ILDs. Information available from the Peek VIDS unit includes the following data: counts, speed, flow rate, headways, and classification (four to five classes). Speed accuracy was not extensively tested against ground truth such as radar or other accurate methods, but district personnel believe Peek speeds to be reasonably accurate.

The primary detection problems experienced by this district are with ILDs. The district just installed six new loop locations where not one of the 20 new loops were accepted by the district. The district had not identified the nature of the problems, but there were indications of bad frequency and high resistance. This could indicate water in ground boxes with improper splices. Saw cutting pavement (he specifically mentioned concrete) causes weakness and failure of the pavement. In the Ft. Worth area, if it rains, the loops change, if it stays dry for a while, the loops also change. The spokesman mentioned the Speedway opening the first weekend in April 1997 and several loop failures on the freeway nearby.

Other technologies that have been discussed include AVI and use of cellular phones for 911 notification of incidents. The district does not think AVI will work well because they do not have toll roads.

3.2.13 Houston District

The Houston District is in the process of installing VIDS systems by Visitech and Autoscope. The district uses a contractor that chooses the VIDS vendor based on how well systems perform in tests. TTI is currently involved in evaluating various VIDS units on Houston freeways, primarily based on counts from the video units compared to manual counts from surveillance video. The manual counts consider occlusion, but there is no adjustment for the comparison. These tests are perhaps the most extensive of any ongoing testing of non-intrusive technologies in Texas. Results of VIDS tests were incomplete at the time of this report, but it is anticipated that VIDS test results will be forthcoming in other reports at a later date. Comments of the TxDOT spokesperson for this report should be considered as preliminary and subject to change upon further evaluation of all factors involved in the testing.

The district currently has two projects that are installing Visitech detectors; one is installing 17 sensor units (cameras) and seven Automatic Control Units (ACUs), and the other is installing 12 sensor units and four ACUs. On another job, a contractor is installing 45 cameras and 15 Autoscope ACUs. The district is also testing a Peek VIDS, but it has not been installed in Houston for actual data collection. On the IH-610 Loop in Houston, the district is installing 83 cameras and 29 Autoscope ACUs. This contract and one other one will cover the entire IH-610 Loop, which is over 40 miles in length. The other contract will include 73 cameras and 28 ACUs, but the video vendor has not been selected. On yet another job that generated its first data April 28, 1997, there were 45 cameras and 17 ACUs.

The Houston District conducted limited testing of the Peek video unit for a 24-hour period on a four-lane freeway section. Results indicated that the Peek performed acceptably based on vehicle count comparisons with manual counts on the first two lanes, but lane 3 and 4 data showed error beyond TxDOT's acceptable range. These tests mounted the camera overhead and off the shoulder. This particular site had substantial truck traffic so occlusion was a significant factor. Peek performance deteriorated at night in comparison to daylight tests. The spokesman's overall comment on accuracy of video detectors was that it depends on careful placement of detection zones. District personnel do not have sufficient experience to know how often the cameras will need repair or adjustments such as "fine tuning" of camera settings.

The data expected to be collected from video units is speed, count, and occupancy data. The software is expected to be similar to that used for inductive loops. Another technology tested in Houston was the Naztech Accuwave (microwave) system. He stated that one problem was that it must be mounted overhead and pointed down at the lanes at a steep angle. In Houston, it is very difficult to find overhead mounting locations. Their mounting locations are likely to be beside the freeway, and according to this person, 12.2 m to 16.8 m (40 ft to 55 ft) high. Finally, a few years ago, the district tested a Microwave TC-30 (pulse ultrasonic technology), but its limited range of approximately 9.2 m (30 ft) was a problem.

When the district contracts loop installation or maintenance on freeways, it typically closes the main lanes and begins work late at night, typically at approximately 10:00 p.m. and continues work until the early morning hours. Some of their problems with loops are due to rotomilling operations. The district is considering including loop replacement with future rotomilling contracts.

One of the primary problems encountered by the Houston District soon after the installation of loops is related to splices. The loop contractor runs the loop leads to a ground box located beside the roadway where a splice is required for home runs to the cabinet. Sometimes these splices are not waterproof. The district goes through and "mags" these loop wires soon after installation for justification of payment. If defective, the district requires the contractor to return to the site and correct problems. After six months to one year, the maintenance section oversees any continuing maintenance activities so costs are difficult to track. The district has considerable problems with loops in asphalt pavements due to pavement weakness and sometimes due to the loop itself. Potholes develop and the loop fails. Even though there are problems with loops, the district spokesman thinks video products will not achieve the accuracy of loops for some time to come.

Replacement of inductive loop detectors in the Houston District is different for concrete pavement and asphalt pavement. When the district routs old loops in concrete, its costs include all replacement costs of loop wire, sealant, and so forth. This is a lower cost than initial installation because the contractor simply uses a thinner blade and cleans out the old saw cuts. It goes much faster than cutting concrete for the first time. Therefore, the linear measurement cost includes both the removal of the old loop and installation of the new loop wire. This will probably not require, for example, replacing leads from the pull box to the controller, so it is not like installing a new loop. If a loop fails in asphalt, the Houston District requires a new loop to be installed beside the old one (they leave the old broken one in the pavement). The bid item is based on length of saw cut, so there are only two wires in the cut except in the loop itself where there are three. This simplifies the bid process -- a contractor only bids for two items: length of saw cut and conduit.

Another important difference in the installation procedure used in Houston that would be different from some other locations is that Houston uses a product called "detecta-duct" in the saw cut. It requires the cut to be wider so prices will probably be higher than some other places. Also, durability might be different.

A typical layout for ground boxes on freeways is one small pull box beside the loops, then one close to the controller cabinet. Their typical maximum distance between pull boxes is approximately 91.5 m to 122 m (300 ft to 400 ft) to make the wire pulls easier. On freeways, they use two loops per lane to monitor vehicular speeds and on frontage roads as part of ramp metering setup.

To determine maintenance cost per month or per loop, one could spread recorded expenditures for loops over their total number of loops; however, this would be very approximate. The district generally assumes that 10 percent of their loops at any given time need maintenance. This could mean only replacing a pull box or replacing the loop wire and nothing else. So a repair would not normally amount to the same cost as an installation.

The prime contractor subcontracts traffic control in many cases and probably adds 30 percent to the bid from the subcontractor. Therefore, traffic control costs provided by the district may not reflect an accurate cost. In the past, TxDOT required some lane closures on Sunday mornings but recently they have been doing this on weekday nights, closing the freeway in some cases and routing traffic onto frontage roads. Table 3-2 indicates inductive loop costs based on one bid.

The following pertains to a spreadsheet printout provided by the district in an attempt to clarify the costs associated with maintenance of inductive loops. This happened to be on intersections only, whereas cost information sent previously was on freeway main lanes. There will be a significant difference in the two because main lane loops must be replaced on weekends or at night, increasing those costs.

The costs in question (for intersections) were monthly charges, and they represent all the repairs made by the district that year. However, they did not do repairs the previous two years nor the next year (1996); therefore, it is not a typical year's worth of failures. The district is limited contractually by TxDOT in Austin to how much maintenance they can do on any given year. The funding amount is apparently set up for smaller districts and is insufficient for large urban districts like Houston.

The number of failures by year are as shown in Table 3-3. There are some difficulties in trying to quantify failure rates over a time period of several years simply because the district has changed its loop policy and equipment over that time period. When it first began installing detectors for signals, the district used quadrapoles in left-turn bays but not on through lanes. Now, it has discontinued the installation of quadrapoles. Beginning two years before this date, the district began using four 1.8 m by 1.8 m (6 ft by 6 ft) loops in turn bays. About three years

Table 3-2. Inductive Loop Costs by TxDOT in Houston

Item Description	Unit	Approx. Qty.	Unit Bid Price	Extension
Replace pull box Type 5 w/exten. (small)	Ea.	10	$200.00	$2,000.00
Install loops in asphalt - main lanes	LF	800	$4.00	$3,200.00
Install loops in asphalt - service roads	LF	500	$3.00	$1,500.00
Install loops in concrete - main lane	LF	800	$3.50	$2,800.00
Install loops in concrete - service roads & ramps	LF	500	$3.00	$1,500.00
Rout out old loops in concrete - main lanes	LF	500	$3.50	$1,750.00
Rout out old loops in concrete - service roads	LF	500	$3.00	$1,500.00
Barricades, signs, and traffic handling (main lanes, 1-lane closure)	Cycle	5	$1,000.00	$5,000.00
Barricades, signs, and traffic handling (main lanes, 2-lane closure)	Cycle	2	$1,000.00	$2,000.00
Barricades, signs, and traffic handling (main lanes, 3-lane closure)	Cycle	2	$1,500.00	$3,000.00
Barricades, signs, and traffic handling (main lanes, 4-lane closure)	Cycle	2	$1,500.00	$3,000.00
Barricades, signs, and traffic handling (main lanes, 5-lane closure)	Cycle	2	$2,000.00	$4,000.00
Barricades, signs, and traffic handling (service roads and ramps)	Cycle	25	$1,000.00	$25,000.00
Boring under roadway	LF	200	$15.00	$3,000.00
Replace detector station/flashing beacon cabinet	Ea	5	$200.00	$1,000.00

prior to this, it began using multiple loops on relatively high-speed approaches to avoid dilemma zones. It stopped installing fixed time signal equipment perhaps 10 years prior to this, but these systems continued operation until approximately 18 to 20 months ago (as of August 1997). The policy is currently being changed again. The current typical loop detector layout is a 1.8 m by 12.2 m (6 ft by 40 ft) loop at the stop bar, but sometimes access to adjoining property is a problem if a curb cut exists within the 12.2 m (40 ft) dimension.

Table 3-3. Number of Failed Loops in the Houston District

Year	No. Failures
1989	42
1990	271
1991	195
1992	211
1993	177
1994	84
1995	208
1996	157[a]

[a] Thru June 1996

3.2.14 Laredo District

The Laredo District has approximately 150 intersections that currently use inductive loop detectors; each intersection has an average of four to six ILDs. Using these numbers, the total number of loops in the Laredo District is between 600 and 900. These loops are used at intersections for presence only, and not for pulse. Another technology used by this district is microwave detectors. There are six of these microwave detectors currently in use. The Laredo District inherited two from the Corpus Christi District on side streets in San Diego, Texas. The Laredo District is also installing these sensors at a new site that is currently under construction. The traffic engineer in the Laredo District used microwave sensors in the Corpus Christi District, before transferring to Laredo, with no problems. A good example of their use was near railroad tracks where the pavement quality is typically poor anyway.

The district has installed VIDS detection in Laredo and elsewhere, totaling 50 cameras, using 16 Autoscope processors and associated hardware. The district contracted to have 14 processors installed along IH-35 frontage roads in Laredo, using two processors at each of seven diamond interchanges. The district also installed four more processors in Del Rio, requiring two processors at each of two interchanges for a total of 18 Autoscope processors currently in use district-wide. The district plans to continue installing Autoscope systems at nine additional interchanges in the near future. Each interchange requires six cameras, so the total number of future cameras to be installed will be 54.

The information being used by the Autoscope units is presence (for use by traffic signals), and counts on each approach. It detects speeds, but the district has not evaluated its speed or count accuracy. The district anticipates that the information stored by Autoscope will provide more insight on actual traffic demands than ILDs. For example, when an incident occurs, there will be data to show frontage road demand for comparison with normal demand. Their typical method of developing timing plans involves conducting a three-day count and extracting the appropriate demand information from that. With more data for different situations, the district feels that it can do a better job of meeting traffic demands. The district did not test the accuracy of the Autoscope systems for two reasons. It was partly because TxDOT personnel in Austin had already determined that they were acceptable and partly because the district was still waiting on different cables to be installed by the contractor to test all the functionality of the systems.

Information collected by these systems goes to the district control center, even though at the present time nothing more is being done with it. Video information from the Autoscopes is similar in quality to the surveillance camera output, so VIDS cameras can double as surveillance cameras even though they cover a limited area. Questions asked of the district (e.g., number of trucks) often cannot be answered except with output such as that available with the Autoscope systems. The traffic engineer stressed that non-intrusive detectors offer one advantage that especially gives them an advantage over others—they do not require substantial interference with traffic.

The Laredo District tried Peek VideoTrak 900 units but they did not perform acceptably during the test period, causing the district to install Autoscopes. The district traffic engineer commented that the Peek system has overcome some of the problems they experienced when they were tested in Laredo.

Problems experienced by the Laredo District with ILDs are similar to other districts. They include interference with traffic, perhaps in small towns at great distances from Laredo. They also include weakening of pavements by the sawing process. The district has had no substantial problems with the Autoscope detectors. One of the critical factors to getting acceptable performance is carefully positioning and aiming the cameras. This can be time-consuming, but a monitor in the bucket truck would facilitate this process. Currently, the district uses one person in the bucket and one at the cabinet. The traffic engineer stated that testing of the Autoscope units indicates that they have overcome previous shadow and wet pavement problems. Austin TxDOT personnel tested one of the Del Rio units to determine the effect of wet pavements and found it counted accurately; it did not double count for headlight reflections and it did not miss vehicles.

The cost of microwave detectors is small relative to video image detection, although the traffic engineer did not know the exact cost. The cost of loops can be very expensive, considering that they can be damaged or destroyed by excavation or other construction/maintenance activities. The traffic engineer stated that the district recently contracted for installation of three intersections at a cost of $20,000. These were later rendered useless by being damaged. The cost of the Autoscope systems was $30,000 per interchange.

One final comment by the traffic engineer was regarding communications, especially at the time upgrades are made. When the Autoscope systems were first installed in Del Rio, the district used telephone lines, later upgrading to ISDN lines. The district did not know how to accomplish the upgrade and apparently were told conflicting information. Besides, there were differences in CODEC systems (brands, etc.) When the district upgrades to fiber optics, it does not want to go through the same difficulties again. Econolite markets a product which was used in Del Rio to send still images, whereas in Laredo they are motion images.

3.2.15 Lubbock District

The Lubbock District has a large number of inductive loops that currently need to be replaced. The district representative currently has a contract for replacing 6,100 m (20,000 linear ft) of loops at a cost of $12.30 per m ($3.75 per ft). The district also has four Accuwave detectors, and they are currently experiencing problems with one of them. The spokesman thinks the problem was a cable that has since been replaced. They have to re-aim the detector and test it to determine if the problem has been solved.

The Lubbock District's problems with ILDs are often due to its own personnel damaging loops by rotomilling or using a grader to level rutted areas and destroying loops in the process. In other cases, cities destroy loops installed by TxDOT. The detectors currently used in the district are only used for signal detection, not to collect or store any type of data. At fully actuated intersections, the district uses presence loops at the stop bar and pulse loops on approaches. The district has not tested the accuracy of Accuwave or ILDs. The Accuwave that has problems shows a call continuously. Other data that the spokesman thinks would be useful include vehicle counts and speeds.

The district does not have very many loop problems except those caused by external forces as described above or in areas that they have been assigned to take over maintenance. An example of this is in Plainview, where many of the loops already installed had failed. In approximately six months, the district will know how many of the ILDs in Plainview failed because the district will make necessary repairs. The spokesman estimated that the Lubbock District has perhaps 10 percent failures at any given time.

There are no technologies of vehicle sensors that this district has used but rejected. Also, there are no technologies that this district is currently considering or testing for possible future use.

One unusual problem that the Lubbock District had was with a re-striping contractor who moved a stop bar. After the change, the loop was in the wrong place and did not detect vehicles stopped in the left-turn lane.

There was some discussion on how to detect intermittent failures and how to determine which of several loops in a small area may be causing a problem. He might have four or five 1.8

m by 1.8 m (6 ft by 6 ft) loops in close proximity and one that is not detecting properly but it is difficult to detect. He goes to the site under low traffic volume (often late at night) and watches the detectors in the cabinet to determine which one is not working. The spokesman does not think the district's ILDs exhibit weather-related intermittent problems.

3.2.16 Lufkin District

The Lufkin District currently has 105 intersections; all but one are actuated. The district uses the following typical scenario for loop sizes and placement: 1.8 m by 18 m (6 ft by 60 ft) at the stop bar, 1.8 m by 12.2 m (6 ft by 40 ft) (or 1.8 m by 9.1 m (6 ft by 30 ft) if shorter turn bay) in the left-turn lane, 1.8 m by 1.8 m (6 ft by 6 ft) on the approaches. These are set up as presence detectors in all cases. The only use for these sensors is for traffic signal operations. In their closed loop systems, they have the capability to monitor speeds and other parameters but they do not utilize the capability.

There is other information that the district will collect in the future. It does not currently utilize all the features of some of their controllers because its current cabinet specification is a limitation. The cabinet is only wired for eight loop amplifiers and the district would like to use their 1.8 m by 1.8 m (6 ft by 6 ft) back loops for extension. The district is developing a new specification for future cabinets to increase its functionality.

Problems with ILDs are typically related to poor pavement condition or thin pavement. Many of the district's roadways have insufficient surface course thickness to ensure good ILD installations. The district recommends placing the loop then overlaying rather than finishing the surface course and cutting into this surface. The majority of the problems stem from the actual construction installation. The district uses a loop contract for replacement of failed loops, and it typically waits until it has eight or 10 failures before having the contractor make the repairs. In so doing, it probably does not detect failures as quickly in back loops as those at the stop bar. When front loops fail, the district feels that it must replace them immediately, but replacement is not as critical on back loops. Problems with loops requiring replacement occur at a rate of approximately eight or 10 every three to four months. This means approximately 30 failures per year.

The Lufkin District gets reliable service out of loops if installed properly the first time; they experience "several years" life from them in that case. The district once tried to use 19 mm (3/4 in) PVC pipe with wires inside. They rotomilled the surface first, then installed the PVC in saw cuts. The district noticed the outline of the loop after a short while and failure occurred because of moisture penetration from rain during construction. The district would also consider prefabricated encapsulated loops, although they too require a wider saw cut than the typical process.

The district spokesman believes that video is cost competitive on a life-cycle basis where a high number of loops are replaced by video image vehicle detection systems. He mentioned that video costs $30,000 to $40,000 per intersection but, based on his experience, the life-cycle cost of loops may be similar to video costs where each camera replaces several loops. He believes preformed loops offer longer life, but if placed in existing pavement also require a wider saw cut.

One technology installed but rejected, at least in the manner used by the district, was microwave sensors. The district mounted these sensors on mast arms so the detectors moved in high winds and generated false detections. The district has not rejected other sensors. This district is considering VIDS as a possible future detection technology. They would consider installing microwave as a temporary detector if ILD failures occur.

3.2.17 Odessa District

The Odessa District currently only uses inductive loop detectors, but they are in the process of evaluating the Accuwave detector distributed by Naztec. The district currently has 42 traffic signals in the district, and an estimated average of eight loops per intersection. Therefore, the district has a total of over 300 inductive loops in the district. It has one site where the microwave sensor is considered to be advantageous—near a railroad at-grade intersection that is only 24.4 m (80 ft) from a traffic signal. Large trucks stop on the tracks waiting for the signal to change and inductive loops would be less practical. Another product the district considered was manufactured by "Lane King" of British Columbia, but its specifications were not as impressive as the Accuwave.

The district uses inductive loops for presence detection on traffic signal approaches. It does not currently collect and store data, although it is just beginning implementation of a closed loop system in Fort Stockton. After it is installed, the district will use the system for data collection and storage. The district currently conducts counts with vehicle counters using pneumatic tubes. Newer signal controllers allow data to be collected within the controller for later download and evaluation for purposes of signal timing.

The inductive loop problems experienced by the Odessa District are similar to those found in some other districts. Their primary problem is with rotomilling operations which destroy loops and their secondary problem is poor pavement. The Odessa District does not appear to have a significant problem otherwise with inductive loops. The district has some locations where loops have been working acceptably for five years or longer, whereas in other locations, loop replacements have been required repeatedly. If the district has a route with heavy truck traffic, they anticipate having problems more often than routes with no truck traffic. Heat is the primary contributor to these problems in asphalt pavement, although the dryer climate in this part of the state is thought to reduce problems. The Odessa area has experienced summer high temperatures as high as 48 degrees C (118 degrees F).

The Odessa District has considerable heavy truck traffic, which contributes to asphalt pavement "shoving" in the vicinity of stop bars and resulting in pavement problems. This shoving of the pavement results in increased stress on loop wires, or creates a need to rotomill, which causes failure. The district loses five to eight loops per year due to "natural" causes and several more than that due to other causes as noted above. When asked about total loop failures, the spokesman started from five years ago. There were six signalized intersections in one town where rotomilling operations were required on U.S. 385. The contractor destroyed all loops when it removed approximately 150 mm (6 in) of pavement then replaced it with fresh asphalt. In Ft. Stockton two years ago, a contractor again removed all loop wires at six intersections with removal of old asphalt. There are four intersections in the town of Kennet scheduled for pavement rehabilitation very soon. Therefore, since 1993, there were a total of approximately 16 intersections with an average of six loops per intersection destroyed. Over this five-year period, there were 96 replacements due to pavement rehabilitation, for an average of 20 per year. The district signal shop now ensures that the contractor includes loop replacement in the contract; otherwise, district personnel have to replace destroyed loops.

The Odessa District has used a loop contract for maintenance and replacement of loops. The spokesman stated that their cost for this contract was $18.86 per linear meter ($5.75 per linear foot) of saw cut. The district has no plans to purchase video imaging equipment because it is too expensive. There are no other technologies that the district has used but rejected.

3.2.18 Paris District

The Traffic Signal Supervisor for the Paris District stated that the district currently uses inductive loops, Microwave detectors, Accuwave detectors, and Rockwell TraffiCams. There are currently 160 intersections in the Paris District, with 130 to 140 of them actuated. It is difficult to estimate the total number of inductive loops because the district has changed its loop configurations over time. At one time, it primarily used 1.8 m by 1.8 m (6 ft by 6 ft) loops, but then it began using longer loops at the stop bar (e.g., 1.8 m by 9.1 m (6 ft by 30 ft), 1.8 m by 12.2 m (6 ft by 40 ft), or 1.8 m by 15.2 m (6 ft by 50 ft)) and 1.8 m by 1.8 m (6 ft by 6 ft) loops as required based on design speeds on the approach. The district's simplest intersection now has eight loops per intersection, whereas at a newer more sophisticated intersection, it may have 26 loops.

The Paris District has two Microwave detectors, one is a TC-26 and the other is a TC-20. They also have one Accuwave detector. The difference is that the Accuwave detects "presence" and the Microwave detects movement. The latter locks in a call so that right turns that clear continue to send a call to the detector (recall feature). Finally, the district purchased three Rockwell TraffiCams to install at three intersections. However, they had only installed one of them due to problems with moisture condensation on the lens. They installed the first TraffiCam because the loops at the intersection had failed and the district needed a quick replacement. For the past year, the district has been working with Rockwell to solve the moisture problems. They removed the detector several times during the one-year period after it was installed to return it to the factory for repairs. The problem has been defective gaskets and seals. Once reinstalled, the system works without fail until a temperature change allowing moisture to condense and penetrate. As far as the Traffic Signal Supervisor knows, this is the first installation for TxDOT because of the problems. Other districts may install after problems are corrected. The spokesman thinks a couple have been installed near Houston.

The Paris District only uses its detectors for signal operation, although it also recently purchased a "counting detector" system from Naztech that interfaces with the signal cabinet that does traffic volume counts. Each of these detectors is left at a particular intersection until traffic counts are finished, then moved to another location. Each unit has the capability of counting more than one lane, and it includes its own loop amplifier.

Problems experienced by the Paris District with ILDs are similar to those encountered by other districts. For example, fire ants and bad pavements cause failures of ILDs. Problems encountered with the TraffiCam systems are as noted above. One problem with the Accuwave detector is not being able to mount it at the end of a mast arm. The manufacturer recommends not mounting it more than four feet from the pole due to deflection in high wind. If the detector moves, it detects motion and sends a "call" to the controller. Also, any tree branches or other movement in its field of view would send a detection. If it were a directional detector, it could filter out some extraneous movement. The Microwave detector is not a presence detector so it must be used in a locking mode.

There are no other detection technologies that have been tried but rejected by the Paris District. For future applications, the Paris District may investigate the Autoscope or other VIDS systems.

Costs associated with the detectors are as follows. Microwave detectors cost approximately $600 apiece; Accuwave detectors cost approximately $800 apiece. The TraffiCam units cost between $4,500 and $5,500 apiece depending upon lens and set-up requirements. One of these units is needed for each approach; the spokesman thinks through movements and right turns can be separated in one unit. The counting detectors noted above cost $147 apiece.

3.2.19 Pharr District

The Pharr District traffic engineer discussed the detection systems installed and planned for implementation in the near future. He estimated that the district has approximately 130 signalized intersections that have inductive loops. The Pharr District has a few closed loop systems, but all other detectors are only for detections and not for storage of traffic count information. Edinburg, Pharr, Falfurrius, and McAllen have closed loop systems. The district is planning other closed loop systems in Brownsville and Harlingen.

The district has not experienced very many ILD failures. One of the things they are doing that they believe reduces stress on the loop wire is bringing the "home runs" from the back side of the loop, keeping them farther from the stop bar where more shoving and rutting occur. In some cases, poor pavement, which is their biggest problem, ultimately results in failure anyway. A few amplifiers go bad, but not often. They plan for rotomilling damage by including it as an item in contracts for resurfacing. The district estimates they experience approximately 2 percent failure rate on their loops due to "natural" causes.

The district is not afraid to try new technologies but it wants to see proof that they work first. They are currently testing an Accuwave microwave detector from Naztech. They placed it on South Padre Island to give it a thorough test in an environment of high traffic and the salt generated from the Gulf. They installed it just prior to the interview, so there were no accuracy results to report. In terms of future tests, they will rely upon another research project to determine the accuracy of the Schwartz Autosense II active infrared detector and the International Road Dynamics SmartSonic acoustic detector. The district plans on installing acoustic detectors on the U.S. 83 freeway adjacent to the district office in Pharr. On the mainline, they still plan on installing ILDs.

The only cost information the district had was on ILDs. The district spends approximately $20 per linear m ($6 per linear ft). The cost of the Accuwave unit they purchased was $1,000 including cable, software, and control panel.

3.2.20 San Angelo District

The San Angelo District has only six intersections with inductive loops, so the number of ILDs maintained by the district totals 26. Of this total, six were installed in April 1997 at approximately the time of the interview. The district has very few problems with inductive loops in terms of "natural" failures; the problems have been with rotomilling operations that destroy the loops. This is a coordination problem, according to district personnel. This statement is understood to mean that TxDOT does not inform rotomill contractors where loops are located and their installed depth. This district does not use a loop contractor; they do all loop maintenance themselves. The district spokesperson did not have cost information on inductive loops.

The San Angelo District is under contract now to install VIDS at two intersections in the district. The district currently has one Peek unit operating at a signalized intersection. It has experienced some problems with the Peek system that initially were thought to be weather related. There are no technologies that the district is currently considering or testing for future use other than video.

All of the detectors used in this district are for traffic signal operation. The district does not store any volume, speed, or occupancy data from these detectors. The only problems expressed by the district spokesperson were an occasional loop amplifier failure. Overall, the district is well pleased with inductive loop detectors.

3.2.21 San Antonio District and TransGuide Center

The following is a combination of various interviews of TxDOT personnel who work both at the TransGuide center and at the district office. The interviews dealing with inductive loops and acoustic detectors are from TransGuide personnel while the interview information regarding video image detectors was from the signal shop supervisor. The San Antonio District deployed two Autoscope systems for temporarily controlling traffic signals on frontage roads. According to the supervisor, the Autoscope "worked fairly well." He stated that its accuracy was in the 85 to 90 percent range. By comparison, the district paid $125,000 for four Visitech units which had both hardware and software problems over the 3 ½-year period during which they were being operated. The district finally discontinued using the Visitech detectors because of these problems. The district recently installed an EagleVision system that the supervisor believes is working well. The district is also awaiting the arrival of CRS video detectors that will be demonstrated in mid-May 1997 by a company from Huntsville, Texas, called Burns Traffic Engineering and Control. If the detection system works acceptably, the district will purchase two systems.

According to TransGuide personnel, there are 591 inductive loops currently being monitored in the TransGuide system in San Antonio. There is also a system of three acoustic detectors mounted on an overhead sign bridge on U.S. 281, although it was not initially part of the TransGuide operation. Acoustic detectors have worked with little or no problems in the three years they have been installed. The TransGuide center has a system monitor that can tell on a lane-by-lane basis when detector malfunction problems arise. Rapid cooling for a period of perhaps 10 to 15 minutes at sundown during the hottest summer months causes ILD monitoring systems to generate alarms, and re-tuning of loop detectors becomes necessary unless they are set to re-tune themselves automatically. The pavement surface reaches temperatures near 54 degrees C (130 degrees F) just before the sun goes down. These temporary problems apparently do not get logged.

ILDs generate presence on single loops and speed and presence on double loops (traps). If the presence reaches three to four seconds, an alarm is generated at the TransGuide center, indicating a possible incident and triggering a camera that turns toward the location. The TransGuide center stores data indefinitely on its mainframe computer on speed, occupancy, and speed difference between adjacent stations. Incident detection algorithms use speed differences to generate incident alarms. TransGuide uses a two-minute moving average on vehicle speeds because of all the spikes in raw data. It collects speed and count data on a continuous basis. The speed accuracy of ILD pairs, as tested by contractor personnel immediately after installation, was within 2 to 3 percent of actual speed as checked by radar. Variations seemed greater during colder temperatures.

A few of the detectors initially installed for monitoring speed and occupancy generated false alarms pertaining to incidents, but TransGuide is in the process of developing a contract for their replacement. So far, none of the freeway loops have been replaced. However, of the total 591 original loops, nine are currently out of service, representing a failure rate of approximately 1.5 percent. Otherwise, problems occur as noted above due to weather. One site needs repair due to unusually dry weather where pavement cracks put excessive tension on loop wires. TransGuide system operators know when a detector goes out because it generates zero speed and 100 percent occupancy when detectors in adjacent lanes show normal conditions.

One of the things the TxDOT San Antonio District has done as a result of cost comparisons is at Lance Jackson at IH-410 where it is using VIDS instead of in-ground loops. Because of construction that caused lane shifts, district personnel believe that video technology is cost beneficial. Total cost information used in this comparison was unavailable, but traffic control costs were discussed. These costs tend to be job-specific, but TxDOT uses a monthly dollar figure once the Traffic Control Plan is agreed upon. Their gross estimate is 3 to 7 percent of the total contract.

The San Antonio District used acoustic detectors on U.S. 281 (even though the initial installation was not part of the TransGuide center) and are planning several additional sites using acoustic detectors in the near future. These detectors, called SmartSonic, were previously marketed by AT&T, but are now marketed by International Road Dynamics. TransGuide personnel believe the cost of these detectors to be very similar to loops. They use one detector per lane which generates speed, occupancy, and volume for the lane. The cost of this detector setup was $5,900, which is similar to four sets of loops (two per lane). Maintenance on the detectors is very easy, according to TxDOT personnel. Cost to install individual loops is $400 to $600 each, but when the detector is as far as 0.6 km (2,000 ft) from the cabinet, it requires an intermediate cabinet. The acoustic sensor does not require intermediate hardware for similar applications. For communication to TransGuide, they implement either of two scenarios: 1) communicate with a common cabinet with a master at the site, or 2) tie directly with the fiber-optic hub.

3.2.22 Tyler District

A representative of the Traffic Engineering section of the Tyler District provided the following information regarding detection technologies used in his district. He had held this position for only one year. The Tyler District has approximately 200 intersections with almost all actuated, resulting in a total of 2,000 inductive loops district-wide. The other two detectors used in the district are Microwave detectors (he thinks TC-20) and Accuwave (also microwave technology). The district has six Microwave detectors installed at intersections, and they just submitted an order for two Accuwave detectors. The district does not have VIDS, although it is interested in using cost-effective alternatives to ILDs that are above the roadway or submerged deeper than loops to prevent damage by rotomilling operations.

The Tyler District only uses the microwave and inductive loop sensors for signal operations, although they would like to get traffic counts as well. The district has not thoroughly tested the reliability of either type of detector, but the spokesman thought the ILDs were 85 percent accurate. This is based on getting a detection at the cabinet every time a vehicle passes over the loop. When the weather changes drastically, the district is required to retune the detectors. The district experiences eight to 10 failures per year due to "natural causes" and 40 to 50 failures per year due to being destroyed by rotomilling operations. Microwave sensors cause problems when they detect movements other than traffic (e.g., tree moving in the wind). Also, they detect movements during rain.

Costs of the Accuwave system are based on two detectors and one board that is required for sensors. Each board will operate two detectors. Detectors cost $750 each and boards cost $350 each. Therefore, a system of two detectors costs $1,850, or on a per-detector basis, $925. The spokesman did not know the cost of Microwave detectors. The Tyler District uses a loop contract for loop maintenance, and the cost is based on length of loop (lineal foot). The cost includes traffic control. Their current contract cost is $23.00 per lineal meter ($7.00 per lineal foot) of loop length (assumes constant width). In other words, a 1.8 m by 18.3 m (6 ft by 60 ft) loop would cost $420 ($7 x 60). The cost of a 1.8 m by 1.8 m (6 ft by 6 ft) loop is approximately $50. The district believes that if the Accuwave sensors last for two years (without requiring major maintenance) they will probably be cost effective when compared to inductive loops.

3.2.23 Waco District

The Waco District has approximately 700 inductive loops. This is based on 120 intersections that are signalized, 70 percent of the intersections are actuated, and an average of eight inductive loops per intersection. The district also has one Microwave sensor that is currently installed in a rural area. The district has a VIDS system by Odetics on Valley Mills Drive at five intersections. Each intersection has four cameras for a total of 20 cameras. The total system cost the district $32,000 for the following items: cameras and lenses, installation, two workstations (one primary and one backup), a laptop computer, and system software. The roadway along this section has four through lanes in each direction and a continuous two-way left-turn lane.

The district is pleased with the accuracy of the system and of the diligence of Odetics in continuing to make improvements. TxDOT has also provided Odetics with input that helps the company improve its system, perhaps encouraging Odetics to provide enhancements. Odetics personnel made several trips to Waco to incorporate modifications. The current detection accuracy for this system is 93 to 95 percent. The district verified this accuracy by using a monitor in the cabinet to receive video from the processor unit and watch for detections as they occurred in real time (lights flashed with each detected vehicle). District personnel did not indicate how large the data sample size was for making the accuracy determination. One problem found during this test that still exists is occlusion from adjacent lanes because of cameras being mounted in a sidefire orientation. This occlusion occurred primarily with tall vehicles such as large trucks.

The detectors in the Waco District are only used for detection. The Valley Mills Drive equipment has the capability of collecting speed and other data but the district is not currently using that capability. One reason the district is not using the full capability of these units is that the contractor continues to modify the detectors in an attempt to improve performance. Actually, the contract period ended eight or nine months ago, but the contractor continued to work with the district to improve their product.

The district initially installed a Microwave sensor (radar technology) in Copperas Cove in an urban environment but it did not operate well at all. The cost was in the range of $200 to $300 for one detector. According to the district spokesman, the sensor detected anything that moved, such as a flag or a tree moving with the wind. It "uses a shotgun approach" in that it does not have a small, fixed detection zone. Instead, it has a large detection area that may detect vehicles, but also pedestrians, animals, or anything else that moves. Therefore, it often gives false detections in a busy environment. In the rural area where it is now installed, it performs very well and was easy to install. The district installed poles and had the system working in two days.

The Waco District is in the process of installing nine Accuwave microwave sensors. They do not have any of these installed currently to discuss accuracy or dependability. The district anticipates that these detectors will be acceptable in situations where loops might not work well. For example, they have one street that is paved with brick where Accuwave should work (the main street is asphalt). In other locations, they have very limited right-of-way, in one case 18 inches behind the curb. They would not install ILDs there because of the space limitations. They frequently run into similar problems in older small towns where loops present special problems. The cost of the Accuwave detectors is $700 each with an interface panel that costs $100. Each panel will accommodate two detectors. Therefore, for each two lanes of detection, the Accuwave system costs $1,500.

Table 3-4 provides the latest cost (August 1997) of ILDs for the Waco District based on the current contract. The ILD price is based on cost per linear meter of saw cut length. For example, the length of a 1.8 m by 1.8 m (6 ft by 6 ft) loop would be based on the perimeter of the loop, or 7.3 m (24 ft). The cost of installing one ILD of this size would be based on a cost per meter of $14.75 for standard 14 gage wire or $18.10 for "loop duct" using 14 gage wire. The cost of a 1.8 m by 1.8 m (6 ft by 6 ft) loop using standard 14 gage wire would be $107.67. Other costs must also be added if ground boxes and conduit are not already installed.

Table 3-4. Current Inductive Loop Costs for the Waco District

Description	Unit	Bid Price
Conduit RM (1 1/4")	meter	$6.60
Conduit (PVC) (SCHD 40)(2")	meter	$9.90
Conduit (PVC)(SCHD 80)(2")(BORE)	meter	$46.10
Ground Box Type A w/Apron	each	$300.00
TRF SIG CBL (Type C)(2 CONDR)(12AWG)	meter	$3.30
VEH DETECT (14 AWG)(BLK)	meter	$14.75
VEH DETECT (14 AWG)(BLK TUBE)	meter	$18.10

In a subsequent phase of this research, TTI will evaluate the cost of inductive loops in a more comprehensive manner for the Waco District. Loop amplifiers are included with cabinets so they are excluded from this computation. The Waco District typically uses 1.8 m by 1.8 m (6 ft by 6 ft) loops in the through travel lanes and 1.8 m by 12.2 m (6 ft by 40 ft) in turn lanes. The district uses 12 gage two-conductor leads from the ground boxes to the cabinet.

The district compared the costs of loops for Valley Mills Drive with the cost of video before installing the Odetics system. This was a situation where they had four travel lanes in each direction and poor pavement, so the video detection systems appeared to be a more viable option. They calculated the cost to be approximately the same for either system.

3.2.24 Wichita Falls District

The Wichita Falls District currently maintains approximately 300 inductive loop detectors at signalized intersections. They also currently own two TC-20 Microwave detectors that are typically used in rural areas for bridge replacements and implementing a one-way traffic scheme crossing the bridge. This plan utilizes one lane of the bridge at a time for alternating traffic flows and traffic signals at each end of the construction site.

The inductive loop detectors are used for detections at traffic signals. The district has closed loop systems in Vernon, Gramm, and Gainesville where it also collects data on traffic volume. These data are used to make decisions on whether to upgrade equipment and adequacy of the signal timing plan. The purpose of the stored data is not necessarily for historical purposes.

The accuracy of the microwave detectors was sufficient for the two applications in which they were used by the district. The district did not check them against inductive loops or otherwise except to observe their performance in a relatively casual manner. For their closed loop systems, the district has the capability of monitoring inductive loops from the office. If a detector output appears questionable, the district sends a technician to the site to check the detector. They sometimes, although not often use a one-hour count at the site to verify accuracy of loops. Most of the time they simply observe their LEDs in the office. The only reason the office observation might not be accurate is on a long loop (e.g., 1.8 m by 6.1 m (6 ft by 20 ft)) there might be multiple vehicles so one blink of the light would represent more than one vehicle.

One of the weaknesses of the TC-20 microwave detector for some applications is that it must mount directly over the lane. The newer TC-26 detector is designed with greater flexibility in this regard. Another undesirable feature of the TC-20 is that it detects vehicles traveling in both directions. According to district personnel relying on vendor information, the TC-26 solves this problem. The district positions it such that they only want detections in one direction. Also, pedestrians or bicycles will sometimes set it off. An example of its advantage is near a railroad track where rail management will not allow boring underneath the track for placement of inductive loops. Thus, the microwave is sometimes an appropriate alternative.

Inductive loops sometimes fail due to poor pavement, especially on city streets which have very thin pavements. The district also experiences rotomilling or other contractor activity that destroys loops. The most recent "natural" failure was four months prior to the interview. This district appears to have better base materials and subgrade than some others so their failure rate is probably substantially lower than others. They also try to bury the loops 63 mm to 76 mm (2 ½ in to 3 in) so that rotomilling operations do not disturb them. The spokesman worked in the Corpus Christi District prior to moving to Wichita Falls and, by comparison, loops last much longer here.

This district is not currently planning on purchasing newer technologies although the director of operations is considering it in the longer range plan. He wants to try VIDS although the district believes the price is still too high to be cost competitive. Their only exposure to VIDS was a demonstration in Dallas attended by their director of operations.

This district has not computed the cost of inductive loops, although the spokesman stated they spent approximately $4,000 on loop failures during the previous year (FY 1996). This included the use of their truck and staff time. Approximately 95 percent of their failures are due to non-natural causes. In Gramm, the rotomilling contractor destroyed 20 loops. That was the third time in 10 years that these particular loops have been destroyed. The district does not use preformed loops.

3.2.25 Yoakum District

The Yoakum District has approximately 135 ILDs at 29 actuated intersections. The district is not currently testing other detectors although various vendors have visited district offices to promote their products. The traffic engineer has made the decision that for the near future the district will not purchase any of the newer technologies such as VIDS and microwave. Inductive loops used by the Yoakum District are not currently used for anything other than for traffic signal control. They are not used for speeds or volume counts. They do not use volume-density equipment.

The district spokesman believes that the information generated by these loops is very accurate. The district only experiences two failures per year on average due to "natural causes." Rotomilling destroys approximately two additional loops per year.

Precautions on ensuring proper operations of loops include making sure all splices and other connections are watertight. Another factor is pavement condition where vehicles, especially trucks, are stopping at the stop bar and the pavement "shoves" causing excess stress in the loops. To reduce the damage done by rotomilling operations, the district is creating a map that shows loop locations so that milling operations will know beforehand if loops exist in the pavement section being worked. The district is also attempting to place loop wire deeper in the pavement at approximately 51 mm to 63 mm (2 in to 2 ½ in) so they are less likely to be damaged. The district used a loop contract for a while but decided to discontinue its use because district personnel believe they pay more attention to details than contractors do.

3.2.26 Summary of TxDOT Districts

Table 3-5 is a summary of findings based on the telephone survey of TxDOT districts.

3.3 OUT-OF-STATE AGENCIES

3.3.1 Central Artery/Tunnel Project

The Central Artery/Tunnel Project in Boston, Massachusetts utilizes approximately 1,400 inductive loop detectors at an initial cost of $400 to $450 each to track vehicles through this section of freeway. The primary function of this loop system is automated incident detection in which the goal is to detect and verify an incident within two minutes. The agency hopes to respond and clear the roadway of an incident within 15 minutes. The installation process placed these loops under the top course of pavement instead of cutting the pavement. The contractor also installed 12 cameras using Autoscope video image detection systems for test purposes. Inductive loop systems collect volume and occupancy data at single loop sites and classification data at dual loop sites. Agency officials have tested inductive loop accuracy by driving a standard vehicle over them to test their tracking capabilities, and they have tested volume count accuracy by conducting manual counts. Comparisons indicate accuracy levels over 90 percent. Agency personnel have not determined how long they need to store data due to the large amount of data collected by the system.

The agency tested a passive acoustic system, which appeared to be sufficiently accurate, but the cost was considered to be excessive. It was part of a formal program that was established to evaluate new technologies. Another system that is generating interest utilizes cellular phones for incident detection as used by the INFORM program on Long Island. Cellular phones have proven so effective that the INFORM program has discontinued use of its incident detection algorithms.

3.3.2 Caltrans New Technologies and Traffic Operations

The New Technologies Division of California Department of Transportation (Caltrans), in Sacramento, in cooperation with the University of California at Berkeley, is funding the development of several vehicle detection technologies, including video, microwave, and laser. Their primary focus has been new developments in inductive loop detection, especially a new system that has the capability of tracking vehicles.

The Caltrans Traffic Operations group is testing the Autoscope video imaging system and the TrafficCAM by Rockwell for possible use in traffic monitoring, incident detection, and general surveillance. Results thus far indicate that the TrafficCAM system does not perform as well as Autoscope. Caltrans is running several tests on detection systems but it has no immediate plans for statewide deployment.

Table 3-5. TxDOT District Vehicle Detection Summary

TxDOT District	Inductive Loop	VIDS	Radar	Microwave	Infrared	Sonic/Ultrasonic	Electronic Toll Tags	Magnetometer	Others
1- Abilene	P								
2- Amarillo	P								
3- Atlanta	P			U					
4- Austin	P	U		U		U			
5- Beaumont	P			U					
6- Brownwood	P								
7- Bryan	P			R					
8- Childress	P								
9- Corpus Christi	P			U					
10- Dallas	P	T		U					
11- El Paso	P								
12- Ft. Worth	P	T	R			T			
13- Houston	P	U	T			T	U		
14- Laredo	P	U		U					
15- Lubbock	P			U					

where:

P = Primary Detector
U = In Use
T = Currently Testing
R = Rejected

Table 3-5. TxDOT District Vehicle Detection Summary (Continued)

TxDOT District	Inductive Loop	VIDS	Radar	Microwave	Infrared	Sonic/Ultrasonic	Electronic Toll Tags	Magnetometer	Others
16- Lufkin	P			R					
17- Odessa	P			T		R			
18- Paris	P	U		U					
19- Pharr	P				T	T			
20- San Angelo	P	U							
21- San Antonio	P	U				U			
22- Tyler	P			U					
23- Waco	P	U		U					
24- Wichita Falls	P			U					
25- Yoakum	P								

where:

P = Primary Detector
U = In Use
T = Currently Testing
R = Rejected

3.3.3 Caltrans District 7 Traffic Management Center

District 7 of Caltrans in Los Angeles uses inductive loops primarily for the detection of vehicles, although volume and occupancy data collected from the loops generate a picture of congestion over the area under surveillance. The occupancy data provide input for incident detection algorithms. The agency believes the data it collects is at most 90 percent accurate, and they check it by visual counts compared to collected data. They would like to collect speed data but are currently using only single loops. The main problem with inductive loops has been traced to faulty installation, but now they believe they have solved the problems.

Inductive loops have been their primary detection method in typical applications, although the district has installed magnetometers on structures due to the undesirability of cutting the bridge deck to install ILDs. They were not favorably impressed with the magnetometer results and are looking for a replacement. They are planning several demonstration projects using microwave and video technologies but had no results to report at the time of the interview.

3.3.4 Caltrans District 11 Traffic Management Center

Caltrans District 11, which encompasses the San Diego area, uses ILDs as their method of vehicle detection. With 300 intersections, 226 ramp meters, and over 100 traffic monitoring stations, the district is responsible for over 15,000 loops. They collect volume, speed, and occupancy data from their detectors and use this data for traffic management, ramp control, signal control, and incident detection. The district stores the data for a few months before transferring it to paper. They do not have an active testing procedure to check the accuracy of their loop detectors. However, they believe that their biggest problem associated with loops is down time, but they do not know what percentage of loops are malfunctioning at any one time.

In general, there is resistance within the district to test or use new technologies, so none have been tested. One exception is a planned demonstration of VIDS within the next several months. The highest priority for use of the district maintenance budget is upkeep of the existing system, relegating testing of new systems to lower importance. Most testing of new technologies is handled at Caltrans headquarters.

3.3.5 Georgia Department of Transportation

The Atlanta, Georgia, metropolitan area has over 1,500 intersections where ILDs are used as the primary detection system. For its freeway monitoring system, the Georgia Department of Transportation (GDOT) has 57 radar detectors and 57 Autoscope processors. Each processor typically accommodates input from six cameras that monitor 8,100 detection zones.

Radar sensors monitor average speed data by direction; they do not collect speed data on individual vehicles. Autoscope systems collect volume, speed, occupancy, and classification data. Data are used for incident detection, freeway management, and signal control. The GDOT

Planning department collects and stores samples of data for historical use at specified locations for up to seven or eight years.

GDOT is concerned about accuracy. Their accuracy goal for historical data stations is 97 to 98 percent. For stations where incident detection or freeway management is the focus, the GDOT believes that an accuracy rate of approximately 85 percent is sufficient. This number could change once GDOT determines the rate necessary for consistent incident detection. The agency is beginning a program of recording several minutes of video from each camera and comparing to manual counts. They field-test the speed accuracy of their radar detectors by using hand-held radar units. Overall, the GDOT spokesman believes that the data they capture is sufficient for their current needs, although he expressed the desire to monitor vehicle occupancy.

Maintenance requirements of the detection systems varied considerably. The GDOT experience with radar indicates that it is a very stable technology. In the case of inductive loops, weather and pavement wear did not significantly increase maintenance costs, but reconstruction and utility work were problematic. Loop life in Atlanta is typically two years.

As for Autoscope, the GDOT spokesman believes that excessive maintenance stemmed from the large size of their deployment, the large amount of data being collected, communication problems with servers, and problems with AC power distribution. The amount of data being collected overwhelmed their servers, and communicating with the servers was also a problem. Error checking of the information being sent during communication failed. The biggest problem was thought to be associated with the distances between cameras and servers. Three phase electrical distribution to the equipment was problematic due to cameras and servers being on different phases of the distribution. The result was cameras not communicating with servers and subsequent system failure. Autoscope personnel expended much time to match up cameras and servers on the same electrical phase. The concern is replacing a transformer with another one on a different phase.

With the Olympics coming to Atlanta in 1996, many equipment vendors tried to promote their products. Fortunately, GDOT was equipped to test new technologies adjacent to their signal shop, located on a high volume frontage road near a signalized intersection. Also important, they were willing to test new technology, but they believe that Autoscope is currently a cost-effective solution to their needs.

The GDOT spokesman estimated that inductive loop costs compared to Autoscope costs for freeway applications is in the range between 18:1 and 25:1 even though he admitted not having complete information to make this estimate. It included costs of an Autoscope server and cameras compared with the loops needed for the same number of detection zones. Motorist delay was not even factored into the freeway cost comparison because inductive loops were cost prohibitive without it. Intersection applications were the complete opposite. Four years ago, Autoscopes cost between $50,000 and $55,000 per intersection, whereas inductive loops cost $500 per loop initially and $1,500 per loop for each replacement.

3.3.6 Boston ITS Program

The ITS Program in Boston, Massachusetts, maintains a small traffic monitoring system utilizing 12 inductive loop stations, eight Whelen microwave radar stations, and two weigh-in-motion (WIM) systems. The detection systems collect volume, speed, occupancy, and weight information. Thus far, the Massachusetts Highway Department (MHD) has stored just over a year's worth of data and have not determined how long they will ultimately store data. The MHD uses output from the loop detectors to check the accuracy of other detectors within the system. They test the radar detectors in a controlled environment before deploying in the field.

One use of traffic data is for incident detection on HOV lanes. Problems experienced with the traffic monitoring systems include piezoelectric sensor failure (used with the WIM systems) and leased telephone lines not relaying real-time data to the central office.

The MHD has considered using VIDS technology but it believes that it is not cost effective. The agency is considering ultrasonic detectors for use in the future. The cost associated with each type of system has not been examined in detail.

3.3.7 Michigan ITS Center

The Michigan ITS Center in Detroit monitors and manages in real time 51.5 km (32 mi) of urban freeway utilizing 1,240 inductive loops. These inductive loops facilitate the capture of volume, occupancy, and speed data, and two-year storage of a daily volume summary at each loop. The agency attempts to detect incidents using detection algorithms and then verifies with the use of 10 closed-circuit television cameras (CCTVs) located around the system. Over the years, the agency has accomplished a significant reduction in the number of loop failures. At one time, they estimated that 40 percent of their loops were not working properly. Since then, they have improved their installation procedure and now believe their failure rate to be 2 percent. They check their loops by measuring the resistance in each loop.

The Michigan ITS Center is currently testing a radar system and an Autoscope video detection system, but results are not available. This is their first attempt to find a replacement or an enhancement to their inductive loop system. Classification data and lateral position of vehicles in the lane are two pieces of information that the center would like to collect.

3.3.8 Road Commission of Oakland County

The Road Commission of Oakland County (RCOC), Michigan, advocates the use of Autoscope 2004 video detection units at all signalized intersections within its jurisdiction. The agency has installed Autoscope detectors at approximately 250 of its total 300 intersections. One camera is mounted over each signalized intersection approach, oriented to face directly downward toward the stop bar. Each Autoscope system is a direct replacement for loop detectors. The RCOC estimates that with the newest version of the Autoscope system they are achieving a vehicle detection accuracy rate of 96 percent. To check this accuracy, the RCOC randomly selects intersections for video taping and subsequent manual count comparisons. Autoscope detections provide input to a SCATS (Sydney Coordinated Adaptive Control System) intersection control system, developed in Sydney, Australia.

The RCOC is attempting to expand the system of vehicle detection by the addition of queue length detection. This requires additional cameras facing upstream to determine the queue length on each approach. This information is then used to supplement the SCATS intersection control system.

The RCOC has experienced problems with the Autoscope, although most of these problems have been solved in recent factory improvements. Problems with shadows and daytime/nighttime transitions have been largely eliminated, and problems due to weather conditions have not been encountered. The poor quality of pavement in the county makes the use of inductive loops impractical. Weather conditions (e.g., freeze/thaw cycles) play havoc with their loops and make them very unreliable.

The RCOC has a program that facilitates ongoing testing of new technologies. When a new product is introduced on the market, the RCOC has capabilities to test and evaluate it against their standards. For example, they examined a radar detector, but rejected it because it did not compare favorably with VIDS. Other products were similar.

The RCOC admits that the initial cost of VIDS is 20 percent greater than inductive loops; however, the additional benefits of video outweigh these costs. The agency has not calculated and evaluated life-cycle costs of competing systems. However, the RCOC is pleased with results from the Autoscope systems.

3.3.9 Minnesota Guidestar

As part of the Minnesota Guidestar project in Minneapolis, there was a two-year test of non-intrusive traffic detection technologies conducted by the Minnesota Department of Transportation and SRF Consulting Group, Inc. Funding for detector testing came from the Federal Highway Administration. The following eight technologies were included in this testing: video, Doppler microwave, radar, active infrared, passive infrared, passive acoustic, passive magnetic, and pulse ultrasonic. This study included two lengths of test periods, one for 24-hour testing and another for multiple week continuous tests. During the extended field tests, the research staff evaluated detectors in a variety of environmental, traffic, and mounting conditions. Testing was primarily on a freeway, but some testing occurred at a signalized intersection.

Because testing was incomplete at the time of the telephone interview, contacts suggested waiting for the final report, which was due to be completed around March 1997. A synopsis of findings by Minnesota researchers is provided in chapter 2.

3.3.10 New Jersey Turnpike Authority

The ILD system used by the New Jersey Turnpike Authority (NJTA), headquartered in New Brunswick, New Jersey, has been operational since 1976 and includes 993 loops. This system utilizes an ILD every 0.8 km (½ mi) in the center lane, on each ramp, and in every lane before and after each interchange. The NJTA is also using 12 microwave detectors and 100 Autoscope cameras. The microwave and Autoscope detectors are mounted overhead on bridges pointed straight down on the roadway. Volume, speed, and classification (car vs. truck) data are collected, but the primary type of information is percent of each minute that each ILD is occupied. It was unclear how long the information was stored but it was assumed to be stored indefinitely. Accuracy is thought to be quite acceptable, except for times when any of the large number of failures occur in the loop system. There are two primary methods used to determine when failures occur. One is by comparing loops with each other, and the second utilizes closed circuit television (CCTV) to compare the view from the field with detector output. A third method, used less frequently, involves dispatching a mobile unit to verify questionable sensor output.

Occupancy rates are examined to determine incidents; then this information is relayed to changeable message signs along the turnpike. The speed limit is controlled upstream of an incident location through the use of changeable speed signs. Lane restrictions on trucks can also be changed to divert them around incident sites.

With the traffic management system the NJTA is using, the type of information it is collecting is sufficient for its needs. The Turnpike Authority would like to stop relying on intrusive roadway sensors, because they have experienced a high failure rate with ILDs. Unfortunately, the exact rate was unknown. The Authority has experienced a problem of double counting with their inductive loop system, which greatly increases the occupancy rate of a particular detector. Construction, weather, salt, and traffic rapidly destroy loops. The only significant problem experienced with their microwave and Autoscope sensors was vandals knocking the sensor out of alignment. No failures of this equipment have been recorded and the only cameras removed were due to construction work on the bridge to which they were attached.

The Authority used magnetometers in the past, but they were ineffective and either failed immediately or were taken off line due to inaccurate results. In the past, AT&T acoustic detectors have been used with good results but their use has not continued. The use of electronic toll tags to replace toll booths is being evaluated. This could lead to the collection of traffic information from toll tags, but this plan is not scheduled to occur in the near future. The Turnpike Authority is also evaluating preformed loops from "Never Fail," which are installed during the overlay process.

3.3.11 Oregon DOT Headquarters

The vast majority of vehicle detection for the Portland Area Traffic Management Center (PATMC) occurs through the use of ILDs. Signal control, ramp metering, automated traffic counts, and traffic management are all accommodated with ILDs. The PATMC collects volume, occupancy, and classification data from the inductive loops. These data are being used for project development, Federal Highway Performance Monitoring System programs, accident rate analysis, and annual volume and classification counts. The Traffic Management Center in Portland is just beginning operations, but it is expected that the data being collected will be used for incident detection and traffic management. Certified technicians supervise and maintain the system so that it continues to meet Federal standards for certain programs. The ILD system is achieving a 90 to 95 percent accuracy rate.

In cooperation with Portland State University, the Oregon Department of Transportation (ODOT) has begun a program to test some of the new technologies in vehicle detection. The program is scheduled to test a Peek VIDS system in the Portland area in the near future. Other technologies have been discussed, but none of those discussions have been acted upon. The only other detection technology used by ODOT is a passive acoustic system being used for detection of aircraft at small airports in the Portland area. According to spokespersons, Oregon is just beginning to learn about new vehicle detection technologies.

3.3.12 Phoenix Traffic Operations Center

The Phoenix Traffic Operation Center (TOC) controls approximately 1,500 ILDs and eight passive acoustic devices. Arizona Department of Transportation (ADOT) plans on installing approximately 200 more acoustic detectors in the near future. The detectors mount overhead on sign supports at a height of 5.5 to 7.3 m (18 ft to 24 ft). ADOT has installed CCTV cameras on 1.7 km (1 mi) spacings for surveillance purposes. The operation center gathers volume, speed, occupancy, and classification data from the detection system. Their system records data every 20 seconds and stores it indefinitely. The agency stores data in three classification bins based on vehicle length: less than 10.7 m (35 ft), 10.7 m to 16.8 m (35 ft to 55 ft), and greater than 16.8 m (55 ft).

In order to verify vehicular counts from acoustic detectors or ILDs, ADOT compares historical data from each site, data from other surrounding sites, and in some cases, tube counters or temporary acoustic detectors. The frequency of calibration of acoustic detectors is every 90 days.

Traffic information gathered from the detectors is used for incident detection. The data are then stored and given to various agencies or groups for various purposes. Users may include Universities (for research purposes), and the Department of Public Safety (DPS) so they can adjust deployment to fit specific problem areas, and to construction firms for planning purposes.

The TOC has encountered the usual problems with ILDs. Most problems stem from poor installation, and it is estimated that approximately 50 ILDs are out of service at any given time. The Center has evaluated the Autoscope VIDS but found it cost prohibitive. It performed adequately but the cost could not be justified. The TOC also tested a radar system but it experienced problems with heavy rains and had a limited coverage area. TOC personnel believe that acoustic detectors are less expensive than ILDs, but they have not thoroughly evaluated costs.

3.3.13 Washington State DOT

Ninety-nine percent of the Seattle area's traffic management system is using ILDs for vehicle detection. The remaining 1 percent is comprised of VIDS, radar, microwave, and infrared technologies. Both signalized intersections and freeways use ILDs. On freeways, they are installed at approximately 0.8 km (½ mile) spacings. The data collection plan collects volume, speed, occupancy, and classification data every 20 seconds to serve as "real-time" data in the Traffic Management Center. These data are necessary for incident detection as well as for posting information on their world wide web site for the motoring public to access. Data processing develops five-minute summaries of the 20-second data that are archived and copied to CD-ROM for indefinite storage. ILD count accuracies are in the 97 to 98 percent accuracy range as checked against manual counts and other nearby ILDs. Other desirable parameters to be measured in their Traffic Management Center include: vehicle density, link travel times, and person occupancy of vehicles.

Washington State Department of Transportation (WSDOT) is testing new technologies to replace ILDs, but nothing has been found that meets the same standards as loops. One of the first detection systems tested by this district and rejected was magnetometers. Maintaining calibration was too difficult, and after a short time period, they failed to detect vehicles. Microwave technologies are being used to detect queues at several intersections but they have also been found difficult to use. Infrared systems are being used to detect oversize trucks near bridges and at rest stops. Radar detectors mounted overhead have produced acceptable detection and speed accuracy results, but the same is not true of either sidefired radar or VIDS. In an overhead, single lane detection situation, VIDS performed acceptably, but in multiple detection applications, VIDS was unsatisfactory.

WSDOT is preparing to test TraffiCAM by Rockwell and a licence plate recognition (LPR) system. The LPR system will measure queue times at international border crossing points and information on shortest delay will be relayed to the motoring public.

WSDOT needs a vehicle detection technology that does not require lane closures for installations or repairs. A sidefire mode is preferable keeping maintenance personnel away from traffic. The cost of closing traffic lanes outweighs the higher costs of some of the new technologies. Therefore, the extra up-front cost of new sensors is worthwhile over the long run.

3.3.14 TRANSCOM

TRANSCOM uses over 700,000 automatic vehicle identification (AVI) tags for vehicle detection and monitoring. The agency expanded an existing system of electronic toll collection readers and transponders to collect discrete travel times and added these data to a continuous update of summary historical data. TRANSCOM is currently undertaking a series of tests to determine the accuracy of the system. Preliminary data indicate that the system is highly accurate. System testing consists of manually timing vehicle runs and comparing results to travel times recorded by the system. The agency uses data gathered from the system for incident detection, O/D studies, diversion routing for buses, and fleet management.

TRANSCOM had several problems when the system was first activated. When upgrading from electronic toll collection to a system that tracks vehicles, many problems with communications occurred; however, these problems were eliminated over time. This expansion eliminated the need for testing other technologies. Results have been so promising during the first two years of use that the agency is expanding the system by a factor of six to eight. Today, there are 22 reader stations that are spaced between 0.8 and 2.4 km (½ mi and 1½ mi) over a 32 km (20 mi) section of highway. Another 75 readers will be installed within 10 months.

3.3.15 Utah DOT

The Utah Traffic Management Division has very limited experience with alternative technologies in vehicle detection, relying primarily on ILDs. A few reconstruction projects have utilized microwave detectors where frequent changes in lane configurations necessitated their use. Utah DOT is testing several Autoscope detectors for ramp metering applications, but agency personnel are concerned with its reliability in certain lighting conditions.

Utah DOT now places most of its ILDs in PVC pipe below the surface of the roadway, reducing failure rates. These detector systems collect volume, speed, occupancy, and classification data. The count accuracy rate of the loops is excellent as verified by video recording and comparison with manual counts. Utah DOT uses the data from its loop system for signal control, ramp metering, and incident detection. The agency estimates installed loop costs at approximately $700 apiece.

3.3.16 Summary of Out-of-State Contacts

Table 3-6 summarizes findings of contacts made with out-of-state users of various detection technologies.

Table 3-6. Out-of-State Vehicle Detection Summary

	Inductive Loop	VIDS	Radar	Microwave	Infrared	Sonic/Ultrasonic	Electronic Toll Tags	Magnetometer	Others
Central Artery Project, Boston	P	T				R			
Caltrans Headquarters	P	T		T					T
District 7, Caltrans	P							U	
District 11, Caltrans	P	T							
Georgia DOT*	P^1	P^2	U	T	T	T			T
Massachusetts Highway Department	U		U						U
Michigan ITS Center	P	T	T						
Oakland Co., Michigan	U	P	R						
Minnesota Guidestar		T	T	T	T	T			T
New Jersey Turnpike	P	U		U		R		R	
Oregon DOT	P	T							
Arizona DOT	P	R	R			U			
Washington DOT	P	U	U	U	U			R	
TRANSCOM							P		
Utah DOT	P	T		T					

P^1 = Intersection
P^2 = Freeway

where:

P = Primary Detector
U = In Use
T = Currently Testing
R = Rejected

4.0 EVALUATION OF DETECTORS

4.1 INTRODUCTION

The following findings on individual detectors are organized by the source: literature, TxDOT district experience, and out-of-state agency experience. Each detection technology has its own section, providing the experience of all available sources in a concise format. The literature section provides results primarily from other field testing by the Minnesota Guidestar Program and Hughes. The primary detection technologies are: video image detection systems (VIDS), passive infrared, active infrared, passive magnetic, radar, Doppler microwave, passive acoustic, and inductive loop detectors (ILD).

Detectors can be generally categorized as either intrusive or non-intrusive. Intrusive detector systems require intrusion into or onto the pavement or roadway during installation. An example of an intrusive detector is inductive loops. Non-intrusive detector systems reduce interference with traffic operations, because they do not require installation into or on the roadway. Non-intrusive systems are installed over the roadway, on the side of the roadway, or beneath the pavement by pushing the device in from the shoulder. Detection technologies discussed below are primarily non-intrusive, although the section begins with ILDs because they are still the most prominent detection system used in Texas and elsewhere.

4.2 DETECTOR PERFORMANCE FINDINGS

4.2.1 Inductive Loop Detectors

4.2.1.1 Literature

Because this research focused on finding replacements for ILDs, the basic emphasis on inductive loops is for comparison purposes. If non-intrusive detector accuracy compares favorably with ILDs and their initial and maintenance costs are similar, there are many agencies that would choose the ILD competitor. Reasons for this include difficulties in closing heavily traveled lanes for maintenance activities, hazardous exposure of workers to traffic, and in some cases long-term maintenance costs of ILDs. The Minnesota Guidestar project *(30)* used six 1.8 m by 1.8 m (6 ft by 6 ft) ILDs installed in previous testing by Hughes for baseline comparison of counts and speed accuracy. Therefore, the inductive loops were only approximately four years old when Minnesota testing occurred. Initial loop accuracy tests showed that the loops in lanes one and two on the freeway undercounted by 0.1 percent, while the HOV lane loops undercounted by 0.9 percent. Speed tests indicated that lane one loops underestimated true speed by 6.1 percent, and lane two loops underestimated speed by 1.9 percent.

4.2.1.2 TxDOT Survey

Several of the 25 TxDOT districts use no detection technologies other than ILDs although almost all districts desire an alternative. Practically all districts use loops only for the purpose of signal detection. Experience with ILDs across the state vary widely because of several factors. Among them are soil types, weather factors, number of large trucks, and ILD installation procedures and policies. Each of these factors may play a part in the accuracy, failure rate, and life-cycle cost of inductive loops. Districts that maintain loops in large urban areas experience much higher traffic control costs and delay costs than districts that are predominantly rural. Costs of loops and comparative costs with non-intrusive detectors will be addressed in more detail in subsequent activities of this research.

The number of ILDs maintained by the various TxDOT districts vary widely, from 26 in San Angelo to 2,000 in Ft. Worth to 4,700 in Dallas. Because almost all districts use ILDs for signal detection, their accuracy must be discussed primarily in that context. Virtually no districts had conducted a comprehensive scientific study although some were relatively confident that their accuracy numbers were reasonably accurate. Accuracy rates experienced by the Abilene, Childress, and Tyler Districts are 90, 97, and 85 percent, respectively. The only contact reporting a speed accuracy was the San Antonio TransGuide Center, which indicated 97 to 98 percent accuracy compared to radar using sets of two loops.

Failure rates were expressed as due to "natural" causes (the ILD system fails) or due to other maintenance or construction activities. Both are important. Failure rates due to natural causes were also highly variable because of reasons already noted. The TransGuide Center reported the lowest failure rate of 1.5 percent, representing nine failures of their 591 loops installed for freeway surveillance. In addition, however, they also experience intermittent failures on a daily basis during hot summer months at sundown. Other districts discussed their ILD failures in terms of percentage malfunctioning at any given time. These districts were: Amarillo — 15 to 20 percent; Atlanta — 10 to 20 percent; Dallas — 3 to 5 percent; Ft. Worth — up to 50 percent; Houston — 10 percent; Lubbock — 10 percent; and Pharr — 2 percent. Not all of these represent failure of the ILD in the road; it could mean shorted wire in the ground box or other minor problem not requiring loop replacement. It should be noted that at least some of the differences in performance are due to the lengths of time they have been installed. San Antonio loops have been installed for a much shorter time than those in Ft. Worth. Some districts were more familiar with the typical ILD life in the district, or their maintenance contract cost in a year. In Austin, a loop typically lasts three to five years and in Beaumont some last 10 years while others last only one year. Brownwood installs six per year, including non-natural causes. Corpus Christi experiences very poor results, with one-year life in new pavement and two- to three-year life in old pavement. In Dallas, the annual cost of ILD replacement is $40,000.

Of the districts providing information on why loops fail, almost all mentioned poor pavement or thin pavement and sometimes large numbers of trucks as contributing to the ILD problem. Rotomilling was consistently the most prominent among non-natural causes. There were a few detector amplifier problems and fire ant problems also mentioned. Loops in poor pavement or thin pavement often resulted in pot holes and large trucks caused asphalt pavement to rut and "shove" in the vicinity of the stop bar. A few districts are using countermeasures such as adding cement to the asphalt mix to provide stiffness and placing the ILD deeper in the pavement to reduce rotomilling damage. Several districts are adding loop replacement as an item in rotomilling contracts so the problem is already covered.

4.2.1.3 Out-of-State Survey

Out-of-state agencies did not provide as much information regarding the accuracy and reliability of ILDs as did the districts. For accuracy, Caltrans District 9 in Los Angeles, Oregon DOT, and Washington State DOT (WSDOT) gave the following accuracy rates: 90 percent, 90 to 95 percent, and 97 to 98 percent, respectively. Caltrans verified their accuracy visually, whereas WSDOT verified their accuracy by manual count methods.

Failure rates of inductive loops by the Michigan ITS Center is 2 percent today, but it has been as high as 40 percent. The New Jersey Turnpike Authority reported a "high failure rate" but they did not attempt to quantify with numbers. They stated that their ILDs have double-counted and that reasons for the many problems include construction and maintenance activities, extreme weather conditions, and de-icing chemicals. Problems are traced to poor installation techniques in Phoenix and Los Angeles and to poor pavements in Oakland County, Michigan.

4.2.1.4 Need for Additional Testing

Inductive loops are a mature technology so additional testing should continue to be associated with comparisons against new non-intrusive technologies. As soon as technologies are found that are as accurate as ILDs in all weather and lighting conditions and exhibit lower life-cycle costs, many agencies will choose the non-intrusive technologies for reasons already noted.

4.2.2 Video Image Detection Systems

4.2.2.1 Literature

Minnesota Guidestar testing included four video systems, the Peek Transyt VideoTrak-900, the Image Sensing Systems Autoscope 2004, the Eliop Trafico EVA 2000, and the Rockwell International TraffiCam--S. One very important finding regarding installation was that mounting video detection devices is a more complex procedure than that required for other types of devices. Camera placement is crucial to the success and optimal performance of the detection device. Lighting variations were the most significant weather-related condition that impacted the video devices. Vehicle shadows, other shadows, and transitions between day and night also impact counting (*30*).

The Peek Transyt VideoTrak-900 is capable of monitoring input from up to four cameras. Initial testing by the research team at the freeway test site resulted in counting accuracy within 5 percent of the baseline ILD system. However, when the device was moved to the intersection periodic failures began to occur and continued throughout the testing. Researchers also observed that overcounting occurred during the light transition periods from day to night and vice versa. Like the VideoTrak-900, the Autoscope 2004 can also monitor input from up to four cameras. Researchers found that the Autoscope is capable of performing within a 5 percent accuracy at both freeway and intersection test sites. Light changes during transition periods also resulted in undercounting by the Autoscope (*30*).

Researchers found that the Eliop Trafico EVA 2000 detection system was capable of very accurate freeway counts, within 1 percent of the baseline. Calibration of this system was difficult as a result of a complicated user interface; however, the system was not inversely impacted by any weather condition and was the only video system that was not affected by light transitions. The EVA 2000 was not recommended for intersection applications so researchers did not supply intersection data. The last video device tested by the researchers was the Rockwell International TraffiCam--S. The TraffiCam required data to be downloaded over the serial connection. Researchers found that the TraffiCam's performance varied greatly during the testing period. Some of the performance problems were attributed to a grime buildup due to salt spray on the camera lens. Shadows and lighting conditions may have affected performance (*30*).

Duckworth et al. (*33*) conducted tests of various traffic monitoring sensors on a highway near Boston. Sensors tested included: video cameras, passive acoustic microphone arrays, active ultrasonic acoustic ranging and Doppler sensors, Doppler radar, and passive infrared sensors. The researchers evaluated and considered the sensor performance, sensor cost, communications required raw data, and the amount of computation needed for signal processing and classification. The researchers found that the video camera provided the best performance in the areas of detection, speed estimation, and vehicle classification. However, they noted that video had limitations in poor lighting and certain weather conditions, and was the most expensive sensor tested (*33*).

4.2.2.2 TxDOT Survey

Video image detection systems (VIDS) are being tested or used in the following TxDOT districts: Austin, Ft. Worth, Houston, Laredo, Paris, San Angelo, San Antonio, and Waco. The Houston results will be published elsewhere. These districts are utilizing a variety of equipment from the various vendors with a range of results. Many of the early shadow and changing light situations have been improved with continued use and enhancements to the various systems. The use of the *Odetics* system, marketed by EagleVision, resulted in the following observations after use. Initial problems in Austin of shadows, night reflections, and double headlight counts have been resolved. San Antonio TransGuide personnel believe their system is working satisfactorily. The installation on Valley Mills Drive in Waco covering five intersections with 20 cameras has improved significantly such that today its detection accuracy (switch closure) is 93 to 95 percent.

The vendor has been extremely generous in providing technical support well beyond the expected period. The district has provided considerable input to this process, which may have encouraged continued improvement.

The Autoscope is prevalent among districts that are using VIDS. The Laredo District installed them in Laredo and Del Rio, but has not evaluated their speed or count accuracy. The traffic engineer believes in spending extra time in setting the camera position and orientation to achieve optimum results. This process would be improved by having a monitor available to the person in the bucket who is adjusting the camera. Today's method uses two persons, with the second person required at the cabinet to watch the monitor and coordinate with the person in the bucket. One advantage of VIDS over other alternatives is having the camera image for surveillance purposes even though it only covers a small area. The cost of the Autoscope system at $30,000 per diamond interchange is also attractive compared to ILDs based on a recent instance in which the district spent $20,000 on inductive loops at intersections and they were destroyed a short time later. The San Antonio District experienced detection accuracy of 85 to 90 percent for two systems installed at intersections.

The San Antonio District purchased four Visitech VIDS a few years ago at a cost of $125,000. The vendor had significant hardware and software problems over the 3 ½-year period of operation in this district, resulting in the district discontinuing their use altogether. The only other district known to have tested this system is Houston but their results were unavailable at the time of this report.

The Ft. Worth District tested the Peek VideoTrak™ 900 VIDS on a freeway comparing inductive loop results with Peek results processed through a Local Control Unit (LCU). The camera was mounted on the outside of the freeway, so its count accuracy was acceptable at only 1.5 percent different from loop counts in a small sample of 200 vehicles. Weather and lighting conditions were very favorable for optimum performance. Count accuracy deteriorated on the next two lanes, falling to within 5 percent of loop counts. It should be noted that this accuracy required considerable fine-tuning, resulting in improvements from 15 percent error to 5 percent error. The only other district known to have tested Peek was the Laredo District. Its performance there was unacceptable, but district personnel believe it has improved considerably since then.

Another VIDS system scheduled to be demonstrated in San Antonio just beyond the time frame of this report was the *CRS* system. Results of these tests scheduled for May 1997 were unavailable.

The Paris District purchased three Rockwell TraffiCam VIDS at a price of $4,500 to $5,500 per approach depending on options needed on each approach. The district experienced repeated problems with moisture condensation on the lens for a period of one year. They returned the units to the factory for repairs, reinstalled them, and they performed acceptably again for a while.

4.2.2.3 Out-of-State Survey

The Boston Central Artery Project purchased for test purposes an Autoscope system that uses 12 cameras, but they did not provide results. The Caltrans New Technologies Division and Traffic Operations Division compared Autoscope and Rockwell TraffiCam, with results to date indicating that the Autoscope system was more accurate. Georgia DOT installed 57 Autoscope processors. Even though problems were reported with power and communications, the agency was pleased with final performance and costs as compared to ILDs. GDOT claimed cost ratios of ILDs to VIDS in the range of 18:1 up to 25:1. They quoted costs of $50,000 to $55,000 per intersection for Autoscope and ILD initial costs of $500 per loop and $1,500 per loop replacement. The Road Commission of Oakland County (RCOC) installed Autoscope at 250 intersections throughout their jurisdiction. The detection accuracy they experienced for signal detection was 96 percent as verified by videotape and manual counts. The RCOC initially experienced problems with shadows and during day/night transitions, but they reported that these problems had since been corrected. They reported the initial cost of VIDS was 20 percent higher than ILDs but they considered the additional functionality to be worth the extra cost. The New Jersey Turnpike Authority (NJTA) installed 100 Autoscope cameras along the turnpike mounted directly over the lanes and pointed downward at a steep angle. The primary purpose of their use was for incident detection. The only significant problem noted by NJTA was vandalism, with cameras being moved out of alignment. The Washington State DOT installed several non-intrusive devices including VIDS, microwave, radar, and infrared detectors and found that nothing meets the same standards as newly installed ILDs. VIDS accuracy was only acceptable when monitoring a single lane with the camera mounted directly over the lane.

4.2.2.4 Need for Additional Testing

There is at least one new VIDS unit that has not been thoroughly tested, at least in Texas. This is the TrafficVision system by the Nestor Corporation. Limited testing occurred in Ft. Worth during the spring of 1997, but this was not as comprehensive as desired for purposes of this research. Therefore, TTI recommends this VIDS system be included in further testing.

4.2.3 Active Infrared Detectors

4.2.3.1 Literature

Preliminary testing by public agencies indicates very promising results for monitoring vehicle speeds and classifications. Active infrared systems appear to be operable during day/night transitions and other lighting conditions without significant problems. An advantage of the infrared sensor is the minimal disruption to traffic during installation or maintenance. Some infrared sensors can be placed at the roadside or overhead on sign structures (*11*). The only weather conditions that appear to be problematic for this device are heavy fog and heavy dust. An application of infrared sensors is detection of overheight trucks approaching tunnels and overpasses, but the more general application is for vehicle detection. Disadvantages of infrared sensors include: difficulties of maintaining alignment on vibrating structures; limitations of across-the-road applications to one-lane roadways; inconsistent beam patterns caused by changes in infrared energy levels due to passing clouds, shadows, fog, and precipitation; lenses used in some devices may be sensitive to moisture, dust, or other contaminants; and the system may not be reliable under high volume conditions. For multilane applications, infrared detectors should be mounted overhead for both speed and volume measurements (*11*). Infrared detectors are used extensively in England for both pedestrian crosswalks and signal control. Infrared detections systems are also used on the San Francisco-Oakland Bay Bridge to detect presence of vehicles across all five lanes of the upper deck of the bridge, thereby providing a measure of occupancy (*15*).

An active infrared device detects vehicle presence by emitting laser beams at the road surface and measuring the time it takes for the reflected signal to return. If a vehicle is present, the return time for the reflected signal will be reduced. The Schwartz Autosense I was the only active infrared device tested by the Minnesota Guidestar project and it was not tested at the intersection location. In addition to detecting stationary and moving vehicles by presence, Autosense I can obtain vehicle speed and vehicle profile (which can be used for classification). One drawback noted was that incoming data are not clearly time stamped (*30*).

The Autosense I system was found to be very accurate at counting traffic at the freeway location, however weather conditions did impact performance of the device. The research team observed that during periods of heavy snowfall, the detector both overcounted and undercounted vehicles. The undercounting was surmised to be the result of vehicles traveling out of the detection zone. The overcounting was attributed to the falling snow reflecting the laser beams causing false detections. Researchers also observed that rain and freezing rain caused overcounting and undercounting. These discrepancies were attributed to the change in reflectivity properties of the pavement (*30*).

4.2.3.2 TxDOT Survey

The only infrared detection system known to be under test by TxDOT was the active infrared system, known as Autosense II, marketed by Schwartz Electro-Optics, Inc. TTI performed testing of this system in research sponsored by the Pharr District *(34)*. One of the infrared detector's strengths is its ease of setup and being able to begin data collection immediately. However, one of its weaknesses is its lack of ruggedness for the rigors of typical field applications. The infrared sensor's operation was intermittent at one point, but the manufacturer remedied the problem. One of the vendor's strengths is in their technical support for solving equipment problems quickly either over the telephone or upon returning the sensor to them. The installer must also realize that Autosense II requires mounting almost directly over the lane. This may require a special pole and mast arm as required in Pharr District testing in Sullivan City.

The detector's list price of $10,000 for one lane of coverage may be a constraint for some agencies, but it should maintain its accuracy in almost any weather and lighting conditions. This statement regarding weather and lighting is based on known characteristics of the technology rather than on sensor testing in this research because TTI did not test this sensor during inclement weather. The speed accuracy of the Autosense II detector is not as consistent as desired for some applications plus its speed data were consistently higher than baseline systems. Its speed bias of approximately 10 km/h (6 mph) can be adjusted through software but its data scatter is also undesirably high. Its standard deviation on speed for a sample size of 158 vehicles was 16 km/h (10 mph), and this was double that of a classification system using ILDs. The classification accuracy of the Autosense II detector was a strength. In a sample of 160 vehicles, it only missed 3 percent and misclassified 7.5 percent, indicating better results than the classifier.

4.2.3.3 Out-of-State Survey

None of the agencies contacted in the out-of-state survey reported using active infrared detectors.

4.2.3.4 Need for Additional Testing

If active infrared detectors need further testing as improvements are made, TTI plans to have one of these detectors installed in College Station at its test site on State Route 6. Also, the one installed in the Pharr District for other research might be available for further testing. At the present time, there appears to be no urgency in continued testing.

4.2.4 Passive Infrared Detectors

4.2.4.1 Literature

Passive infrared devices use the measurement of infrared energy radiating from a detection zone to detect the presence of vehicles. Researchers found that passive infrared technology performed well at both freeway and intersection testing locations and is a good technology for monitoring traffic in urban areas. The passive infrared devices tested during the Guidestar test were the Eltec Models 833 and 842, and the ASIM IR 224. The researchers found that passive infrared devices were not impacted by weather conditions and were very easy to mount, aim, and calibrate. However, there were significant differences in performances of the devices tested (*30*).

The Eltec Models 833 and 842 are self-contained passive infrared detectors, that are easy to mount and calibrate. The Eltec models, which are designed to be mounted either overhead or slightly to the side of the roadway, can be used to monitor either oncoming or departing traffic. However, repeatability was an issue and in some instances it had significant fluctuations in count accuracy. The best performance of the vehicle occurred during a 24-hour test when the device counted within 1 percent of baseline data (*30*).

The ASIM IR 224, which is designed to be mounted either overhead or slightly to the side of the roadway, must face oncoming traffic. This passive infrared detector monitors three measurement zones and a vehicle must pass through all three zones in order to be counted as a detection. The IR 224 was easy to mount and calibrate, and repeatability was good. One device was observed to undercount vehicles during snowfall, however this miscounting may have been the result of vehicles traveling outside of the sensor's detection zone. The results of this device during an optimal 24-hour count period at both the freeway location (within 1 percent of baseline data) and the intersection (within 2 percent of baseline data) were among the best results obtained (*30*).

Both the Hughes Aircraft Company *(31)* and Duckworth *(33)* included passive infrared detectors. However, neither gave the detectors tested exceptionally high marks in their evaluations and conclusions.

4.2.4.2 TxDOT Survey

No TxDOT districts reported having tested or installed for continued use any passive infrared detectors.

4.2.4.3 Out-of-State Survey

No out-of-state agency contacted by TTI reported having tested or installed for continued use any passive infrared detectors.

4.2.4.4 Need for Additional Testing

The passive infrared detectors appear to be worthy of consideration as a detection technology, but recent tests should be sufficient for making decisions regarding their use.

4.2.5 Radar Detectors

4.2.5.1 Literature

Minnesota Guidestar researchers tested one radar device. The radar device tested by researchers was the EIS RTMS. This device can be mounted either overhead or in a sidefire position and can be aimed perpendicular to traffic. The RTMS was easily mounted but required a moderate amount of calibration to achieve optimal performance. The researchers found that rain affected the performance of RTMS, although this degradation was attributed to water entering the device and not to limitations of the technology. When RTMS was used in an overhead mounted position the device undercounted vehicles by 2 percent or less at the freeway site. When RTMS was in a sidefire position the device undercounted by approximately 5 percent. RTMS was not tested at the intersection site (*30*).

4.2.5.2 TxDOT Survey

The Ft. Worth District tested the RTMS radar detector by Electronic Integrated Systems, Inc. of Canada. Their initial reaction was that its software was difficult to use. In terms of detection results, their test location which had vertical concrete retaining walls on each side, created erroneous readings from this unit. District participants hypothesized that deflected radar beams bouncing off the retaining walls greatly altered the radar's typical operations and resulted in erratic performance. They recommended not using radar technology in this situation. The Houston District also tested the RTMS detector, but its results are not published at this time.

4.2.5.3 Out-of-State Survey

Georgia DOT installed 57 radar detectors which monitor average speed by direction; they do not collect speed data on individual vehicles. The Road Commission of Oakland County tested radar detectors but did not think they compared favorably against VIDS. The Phoenix Traffic Operations Center tested radar units, but they noted problems during heavy rain and the radar had a limited coverage area. The Washington State DOT installed several non-intrusive devices including VIDS, microwave, radar, and infrared detectors and found that nothing meets the same standards as ILDs.

4.2.5.4 Need for Additional Testing

TTI recommends additional testing of EIS RTMS in Texas to supplement the limited testing conducted in Ft. Worth.

4.2.6 Microwave Detectors

The Federal Communications Commission allows microwave frequencies of traffic data collection devices in the 10.5 to 24.0 gHz (gHz = 10^9 hertz) range. This range is within the typical range of electromagnetic radiation associated with microwave of 10^9 to 10^{11} hertz. Microwave detectors are categorized as either Doppler or radar devices. Pulse microwave, or radar devices, measure the time it takes for a portion of the microwave radiation to be reflected from the target area to a receiver. Continuous microwave devices, or Doppler devices, output a continuous signal to the detection zone and use the Doppler principle to analyze the change in frequency of the reflected signal to calculate the speed of the vehicle. Doppler microwave devices can detect volume, presence, and speed; whereas pulse microwave devices can detect volume, presence, and occupancy *(30)*.

4.2.6.1 Literature

Four different Doppler microwave devices were tested, but the research team presented detailed data for only two of the devices. The devices tested were the Peek PODD, the Whelen TDN-30, the Whelen TDW-10, and the Microwave Systems TC-26B. The research team found that all four devices were easily mounted and calibrated, and that none of the devices seemed to be affected by weather conditions. However, the devices tested revealed differences in performance. The study did not provide data for either the Whelen TDW-10 or the Microwave Systems TC-26B (*30*).

Researchers found that under optimal conditions the Peek PODD was able to count vehicles at the freeway site within 1 percent of the baseline, provided that the device was properly aimed. The PODD requires that mounting be either overhead or slightly to the side of and facing oncoming traffic. These mounting requirements resulted in poor aiming of the device which may have led to undercounting during one test and overcounting during another. During one of the procedures it was observed to detect vehicles in the adjacent lane. The PODD was not able to collect good data for the intersection site. The Whelen TDN-30 also requires that mounting of the device be either overhead or slightly to the side of and facing oncoming traffic. The primary role of the device is to collect speed data. Researchers found that the device undercounted vehicles at the freeway site by approximately 3 percent and was not able to collect meaningful data at the intersection site (*30*).

4.2.6.2 TxDOT Survey

Two Doppler microwave detectors were found to be very prominent in TxDOT districts, the Accuwave detector and the Microwave detector. A total of 16 districts are currently evaluating or have purchased and installed one or both of these detectors, so they are among the most popular non-intrusive detectors being used. The Austin District experience indicates that fog and rain diminishes performance of their Microwave detector, and the detectors "lock" a call. So, when a right-turning vehicle is detected, it will be given a green even though it may have already cleared the intersection. Beaumont and Tyler Districts only use Microwave detectors on minor side streets, but background movement generated false detections. The Bryan District's Microwave detector only lasted a few months and failed. The Laredo District is using microwave technology at rail crossings and has noted no problems with performance in this application. The Lufkin District mounted Microwave detectors at the end of signal mast arms and there was too much movement, generating false detections. The Paris District considered the cost of a Microwave detector at $600 apiece as one of its attractive features. The Waco District first mounted its Microwave detector in an urban area, but it generated too many false detections. It later moved it to a rural area and the district is now very pleased with its performance plus its ease of installation. The Wichita Falls District uses Microwave detectors in rural areas for bridge replacements where one lane of traffic is maintained. However, the TC-20 detector's disadvantages include 1) it detects both directions of traffic and 2) it must be mounted directly over the lane. According to vendor information, the TC-26 is more flexible in mounting requirements.

The Atlanta District reported that their three Accuwave detectors generate false calls when anything such as tree limbs or animals pass or move within the detection area. The Corpus Christi District has 51 Accuwaves but their experience indicates difficulty in optimizing performance. The Houston District is testing the Accuwave, but its requirement of being mounted directly over the lane creates difficulty in Houston. The Lubbock District has experienced problems with one of its four Accuwave detectors, but it appears to be a bad cable. The Paris District tried the Accuwave at the end of a signal mast arm, but the movement generated false detections. The manufacturer recommends placement no further than four feet from the pole. The cost of Accuwave detectors is one of its attractive features. The Tyler District bought two, at a per-lane cost of $925. This consists of $750 per detector and $350 for the board that accepts up to two detectors. This district considers a two-year life acceptable for these detectors. The Waco District purchased nine Accuwave detectors, which were just installed so performance was not available. They paid $700 each for them and $100 for the board, so their per-lane detection cost was $750.

4.2.6.3 Out-of-State Survey

The Washington State DOT installed several non-intrusive devices including VIDS, microwave, radar, and infrared detectors and found that nothing meets the same standards as ILDs.

4.2.6.4 Need for Additional Testing

Based on the widespread interest by TxDOT in two microwave products, TTI recommends additional testing of one or both of these. The emphasis should be place on the Accuwave detector because its test results were not available in the literature reviewed.

4.2.7 Passive Acoustic Detectors

4.2.7.1 Literature

The SmartSonic TSS-1 provides a detection zone size of 1.8 m to 2.4 m (6 ft to 8 ft) in the direction of traffic, and provides one or two lane selectable zone size in the cross lane direction. The TSS-1 processing in the controller card has the capability of computing traffic flow measurements such as vehicle volume, lane occupancy, and average speed for a selectable time period. In limited testing, the speed accuracy for the acoustic detection system was plus-or-minus 10 percent when compared to inductive loop detection systems. Power requirements for the system are low, 5 to 6 watts, which will allow the use of solar panels. The cost of the acoustic sensor is $1,450 per unit, with one required per lane per detection location. The detection system also requires a controller card at a cost of $800. Each card can accommodate up to four acoustic sensors. The system which can be mounted in either a sidefire or overhead configuration has minimum mounting requirements of 6.1 m (20 ft) overhead and 7.6 m (25 ft) horizontal distance from the travel lane. Available information indicated that weather conditions, other than very dense fog, do not interfere with the system detection capabilities.

Minnesota researchers found that the optimum position for passive acoustic devices is the sidefire mounting position with microphones aimed at the tire track because the primary source of sounds for vehicle detection is the noise generated between the tire and road surface. In Minnesota tests, the devices were mounted sidefire and were noted to be relatively easy to install and calibrate. Low temperatures and the presence of snow on the roadway, which may have muffled sound, were both correlated with undercounting by the devices. When the SmartSonic devices were mounted on the freeway bridge undercounting daily traffic ranged from 0.7 to 26.0 percent. This undercounting was attributed in part to the echo-filled environment underneath the bridge. Researchers found that both SmartSonic devices undercounted vehicles during freeway testing and overcounted at intersection testing (*30*).

4.2.7.2 TxDOT Survey

Other detector research by TTI sponsored by the Pharr District included the SmartSonic acoustic detector. Its primary application in this research was detecting trucks approaching isolated signalized intersections *(34)*. The cost of the acoustic detector system for two lanes was approximately $5,000. The TTI experience with this detector was somewhat limited because of early difficulties in properly mounting the detector and equipment problems. The detector has been marketed as a vehicle speed and count detector for a longer period of time. Based on tests in the Pharr District at Sullivan City, the SmartSonic detection system misclassified approximately 20 percent of vehicles as compared to a vehicle classification system using ILDs. Its total vehicular count (all classes) for an 11-hour period was 15 percent lower than the count by the classifier system. Every hour of this period was lower, by as much as 20 percent, compared to the classifier.

Analysts could not verify its classification accuracy specifically relating to trucks because its classes did not correspond to those of the classifier system. However, based on the comparisons that could be made with a reasonable degree of accuracy, this system is currently unsuitable as a truck detection system. Its speed values were consistently higher than the ILD system. For example, in a data set of approximately 2,000 non-trucks, its mean speed was 6 km/h (4 mph) faster than the ILD system. Standard deviations were exactly the same for both systems at 12 km/h (7 mph). A much smaller data set indicated a larger discrepancy for truck speeds -- the acoustic mean speed was 13 km/h (8 mph) faster than the ILD mean value. The standard deviation was also higher for the acoustic at 18 km/h (11 mph) versus 12 km/h (8 mph) for the classifier.

An advantage of the acoustic detector in comparison to detectors always requiring overhead mounting is the fact that it can be mounted on a pole beside the roadway in some applications. However, monitoring two side-by-side lanes is probably best handled with an overhead support.

4.2.7.3 Out-of-State Survey

The Boston Central Artery Project tested passive acoustic detectors, but considered the price to be excessive. The New Jersey Turnpike Authority used acoustic detectors with what they considered to be reasonable results, but discontinued their use after some time. The Phoenix Traffic Operations Center installed eight acoustic detectors for an evaluation period and decided to install 200 more acoustics. Phoenix personnel believe the acoustics are less expensive than ILDs but they have not conducted a formal cost comparison. The operations center collects volume, speed, occupancy, and calcification data from the detection system.

4.2.7.4 Need for Additional Testing

As improvements are completed to the classification module of the SmartSonic system further testing will be warranted. Based on limited testing in the Pharr District and comparison against an ILD classifier, this detector needs additional improvement to its classification algorithm. TTI only tested the basic default settings as recommended by the manufacturer and established the aim of the detector as recommended by the manufacturer. TTI did not attempt to optimize performance by additional sensitivity adjustments or aiming adjustments.

4.2.8 Pulse Ultrasonic Detectors

4.2.8.1 Literature

The Minnesota research team tested two pulse ultrasonic devices, the Microwave Sensors TC-30 and the Novax Lane King. Overhead mounting of the device provides optimal signal return and vehicle detection; however, sidefire mounting is possible for some devices. Pulse ultrasonic devices are relatively easy to mount; however, the ease of calibration varies with devices. Weather conditions did not impact the performance of the devices (*30*).

The TC-30, which may be mounted either overhead or sidefire, was found to provide an accurate vehicle detection count at the freeway test site and a tendency to overcount at the intersection test site. The TC-30 was easy to mount and calibrate. Researchers observed that vehicles stopped in the detection area were counted multiple times resulting in the overcount. The Novax Lane King can also be mounted either overhead or in a sidefire configuration. The Lane King was easy to mount; however, calibration was extensive for optimum performance. The Lane King was extremely accurate in counting vehicles at the freeway site, but at the intersection site overcounting occurred as the result of double counting. The two pulse ultrasonic devices interfered with one another when mounted next to each other (*30*).

4.2.8.2 TxDOT Survey

The only TxDOT district indicating any experience with the TC-30 was the Houston District and their only comment was regarding its limited range of approximately 9.2 m (30 ft). No other TxDOT districts reported testing or installing pulse ultrasonic detectors.

4.2.8.3 Out-of-State Survey

There were no out-of-state agencies who reported testing or installing pulse ultrasonic detectors.

4.2.8.4 Need for Additional Testing

The pulse ultrasonic detectors appear to be promising from previous testing. However, the testing already completed appears to be sufficient to make appropriate judgments about the technology. Therefore, TTI does not recommend additional testing in Texas.

4.2.9 Other Detectors

There was other limited information on detectors or techniques being tested or implemented for monitoring traffic. These systems may be applicable in more limited situations where those discussed above might not be as appropriate.

4.2.9.1 Literature

Passive magnetic devices measure the change in the earth's magnetic flux created when a vehicle passes through the detection zone. It can be compared to an inductive loop, which is an active magnetic detector. With ILDs, a small electric current is applied to a coil of wires, and detection occurs by the changes in inductance caused by the passage of a vehicle. For example, a microloop detection system is a passive sensing system that is based on the earth's magnetic field. When a vehicle passes through the detection zone, it temporarily distorts the earth's magnetic field (*9*).

Passive magnetic device must be relatively close to the vehicles it is detecting, therefore most applications of this type of device require installation below the pavement or in a sidefire mode. Two magnetic devices were tested during Minnesota Guidestar testing, the Safetran IVHS Sensor 231E and 232E Probes. Two Safetran 231E Probes were installed in conduits underneath the roadway and were connected to the IVHS Sensor 232E, a processing card located in a collection trailer. Volume, speed, and occupancy can be calculated from the detector data. The data from the probes, which were located approximately 6 m (20 ft) apart, could also be used to calculate speed. Installation of the passive magnetic devices were difficult and required several days. Water was also observed to be captured in the conduit and at the handhold area of the conduit, which possibly resulted in problems with the probe's performance (*30*).

The probes demonstrated erratic performance which could be due to intermittent grounding problems. The problems were observed during periods of rainfall. Snow and rain also affected detector performance. Overcounting during periods of snow was attributed to vehicles leaving the detection zone. Problems with rain were surmised to be due to water entering the conduit handhold and shorting out the probe connections at the splice (*30*).

4.2.9.2 TxDOT Survey

TxDOT districts did not report any passive magnetic devices, but one district used an active magnetic device. Its experience with microloops indicated performance that was not acceptable, plus these detectors required a proprietary board in the cabinet, making it even less desirable.

4.2.9.3 Out-of-State Survey

Caltrans District 7 in Los Angeles tested magnetometers on bridges where ILDs were not feasible. Their results were less than desirable. The New Jersey Turnpike Authority installed magnetometers on its facility. Some failed immediately and others were so inaccurate that they were subsequently taken off line.

Another technology that is being used in a few large urban areas involves the use of automatic vehicle identification (AVI) tags. Vehicles with tags that are read periodically as the vehicle travels along a roadway serve as "probes" that provide link travel speed information to a control center. The same tags are also available for use in toll applications. TRANSCOM is using 700,000 AVI tags to monitor link travel speeds. Preliminary data indicate that this method is highly accurate.

4.2.9.4 Need for Additional Testing

There is no need at the present time for further testing of magnetic devices. The only exception might be a new device that appears to be promising from an accuracy and reliability viewpoint and is cost competitive when compared against other alternatives.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

There is little doubt that there is a tremendous need to find detection technologies that offer replacement potential for the traditional inductive loop detector (ILD). Loops are a mature technology, having been in use for many years, so transportation engineers should not expect newer non-intrusive detectors to initially replace loops in all cases. New technologies are already offering benefits over loops; however, none of the newer technologies are as accurate as properly installed and functioning ILDs in all weather and lighting conditions.

Results of new detector testing clearly indicate promising alternatives to ILDs but the limitations of these new detectors must also be accepted. An important part of the decision process will be a life-cycle cost analysis comparing inductive loops with newer alternatives. The next phase of this research will include such a comparison. Another important consideration with the potential proliferation of various technologies is the compatibility of data communication protocols being sent to Traffic Operations Centers throughout the state. TTI researchers are currently involved in research requiring communications between three detectors, an active infrared, a passive acoustic, and an ILD-based classifier and a signal controller cabinet. This difficulty will also be reduced by the newer generation of Advanced Traffic Controller ATC 2070. Addressing communication protocols will also be included in the next phase of the research. It is anticipated that ongoing NTCIP activities will provide some of the necessary input, but TTI researchers are poised and ready to customize detector protocols to the specific needs of TxDOT.

5.2 CONCLUSIONS

According to Hughes Aircraft results, the Doppler microwave detectors provided the best performance for gathering specific data for most categories; however, it should be noted that this detection technology does not detect stopped vehicles. Researchers found that the Doppler microwave, true presence microwave, visible VIDS, SPVD magnetometer, and inductive loop technologies performed well for low volume counts. The Doppler microwave, true presence microwave, visible VIP, and inductive loop performed well for high volume counts. The Doppler microwave was the best performing technology for low volume speed and for high volume speed. The Doppler microwave, microwave true presence, SPVD magnetometer, and inductive loop technologies performed best in inclement weather *(31)*.

Duckworth et al. (*33*) conducted tests of various traffic monitoring sensors on a highway near Boston. Based on testing a number of technologies along with sensor performance, sensor cost, communications requirements, and amount of computation required, researchers found that the VIDS provided the best performance in the areas of detection, speed estimation, and vehicle classification. However, they noted that video had limitations in poor lighting and certain weather conditions, and was the most expensive sensor tested. Pulsed ultrasound was found to be the best sensor for detection and classification when cost, the communications bandwidth requirements, and processing power are considered. Radar was the best velocity sensor for vehicles it detected. The researchers recommended that a combination sensor of pulsed ultrasound and either pulsed-Doppler ultrasound or Doppler radar be considered as the strongest candidate as an inexpensive replacement of magnetic loop detectors (*33*).

5.3 RECOMMENDATIONS

5.3.1 Detection Systems

Based on the literature review, the survey of districts and out-of-state agencies, and field testing in other ongoing research endeavors, the research team recommends additional testing of a few detectors. There is one relatively new VIDS product that has not received comprehensive testing in Texas. It is the TrafficVision by the Nestor Corporation. Another detector that needs further testing uses microwave technology, the Accuwave detector, marketed by Naztech. Another detector that has not received full testing is a radar detector, the RTMS by Electronic Integrated Systems.

5.3.2 Detector Test Procedures

The procedure to be used for field testing new detectors is very critical to the outcome of the test. Future testing may be single or dual-staged, but it should always utilize the same site. A good location for initial testing is the TTI site on State Route 6 in College Station for freeway tests and another site to be named on Wellborn Road, also in College Station. For a freeway with the full range of volumes and speeds, Loop 1 (Mopac) in Austin offers the proper conditions. TxDOT has begun installing a verification system for this purpose. However, the site requires proper supplemental instrumentation, to include two inductive loops in each lane on the mainline. Their data storage equipment should be designed to minimize time-consuming and labor-intensive human data analysis.

There should also be a laboratory procedure developed to test basic parameters as appropriate for each technology. Consideration should be given to temperature and humidity extremes, vibration, electromagnetic interference, communications requirements, and voltage variations. A more comprehensive list of parameters and exacting standards needs to be formulated to thoroughly test each new system or modifications to existing systems.

These test procedures should supplant individual district testing with few exceptions. Currently, various districts conduct their own evaluations of detectors, causing redundancy in testing activities. The Traffic Operations Division of TxDOT should establish criteria where testing would still occur in districts, but there should be a methodology for sharing knowledge gained with all other districts. The establishment of a formal test program should also include anticipated costs, both directly to the department in staff time and other resources as well as contracts with universities to conduct the necessary laboratory testing.

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7.0 APPENDIX

SURVEY FORM

Date: ____________________
Name: ____________________
District: ____________________
Address: ____________________

Phone Number: ____________________
Fax Number: ____________________
e-Mail Address: ____________________

Question # 1

Would it be possible for researchers to visit your facilities to observe and learn about your operating procedures?

Questions # 2 & # 3

1) What type of vehicle sensors are currently in use in your district?
2) How many of each type?

Type		Number
Inductive Loop		
Magnetic		
Piezoelectric		
Microwave		
Radar		
Laser		
Infrared		
Passive Acoustic		
Ultrasonic		
AVI		
Tripwire Video		
Tracking Video		
Other		

Question # 4

a) What type of information do you gather from these sensors?
b) How long do you store this information?

	Type	Length of Storage
Volume		
Speed		
Occupancy		
or Density		
Classification		
Others		

Question # 5

a) How accurate is the information that you are receiving from the vehicle sensors that you are currently using?

b) How has this accuracy rate been verified?

c) Why do you need the accuracy rate that you are trying to achieve?

Question # 6

What is done with this information?

Question # 7

Are there some types of information not currently collected that would be useful?

Question # 8

a) What type of problems have you encountered with each type of sensor?

b) How often do these problems occur?

Question # 9

Are there technologies of vehicle sensors that you have used but rejected?

Question # 10

Are there technologies that you are currently considering and/or testing for possible future use?

Question # 11

What are the costs associated with each type of sensor used in your district?

Traffic Control
Maintenance
Capital Costs
Motorist Delay

Question # 12

What are your opinions and/or experiences with the different types of sensors?