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16. Abstract

One research area that has the potential to both improve operations and safety and alleviate infrastructure and maintenance demands from both U.S. and Mexican trucking activities is improved signal operations in rural areas—especially at isolated intersections. Recent advances in sensing technologies and signalization enable more efficient and safe intersection control. In this application, video imaging, or other sensing technology with the capability of differentiating trucks in the traffic stream, and priority algorithms running on computer-based systems that work with existing controllers (or the use of advanced controllers that have their own computer capabilities) may be used as a system that guarantees green time (nonstop conditions) to trucks within some specified distance threshold of the intersection. This research entailed the implementation and analysis of sensing technologies at isolated intersections with high truck volumes and focused on the potential benefits of sensing trucks approaching such an intersection and a priority system that reduces stops to trucks or provide trucks sufficient time to stop comfortably.

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EVALUATION OF INNOVATIVE METHODS TO REDUCE STOPS TO TRUCKS AT ISOLATED SIGNALIZED INTERSECTIONS

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at Isolated Intersections

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IMPLEMENTATION STATEMENT

The objective of this research study is to evaluate the feasibility of and demonstrate the application of a traffic signal system to reduce delays to commercial vehicles at isolated intersections. The implementation recommendations for this project are found in chapter 8.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

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SUMMARY

One research area that has the potential to both improve operations and safety and alleviate infrastructure and maintenance demands from both U.S. and Mexican trucking activities is improved signal operations in rural areas—especially at isolated intersections. Recent advances in sensing technologies and signalization enable more efficient and safe intersection control. In this application, video imaging, or other sensing technology with the capability of differentiating trucks in the traffic stream, and priority algorithms running on computer-based systems that work with existing controllers (or the use of advanced controllers that have their own computer capabilities) may be used as a system that guarantees green time (nonstop conditions) to trucks within some specified distance threshold of the intersection.

This research study entailed the implementation and analysis of sensing technologies at isolated intersections with high truck volumes. The study focused on the potential benefits of sensing trucks approaching such an intersection and a priority system that reduces stops to trucks or provide trucks sufficient time to stop comfortably. The work plan for this study consisted of eight specific research objectives including: a literature search and review; an evaluation of available technologies, selection of equipment to test, purchasing the equipment, making any modifications to the equipment that are necessary, testing the prototype system, selecting the site and field testing the prototype system in TxDOT's Pharr District.

The original equipment purchase plan proposed buying video image detection system (VIDS) equipment to detect trucks and meet other project objectives. However, an early finding was that no video image system equipment could classify vehicles in all lighting conditions. The VIDS equipment typically classifies vehicles in daylight based on length, but at night this equipment reverts to detection of headlights only, and VIDS cannot distinguish truck headlights from car headlights. Therefore, researchers conducted a telephone survey to determine candidate systems that possessed the following characteristics: generate vehicle-specific data that can be interpreted from their serial communication port, can determine speed and vehicle class accurately, are reasonably priced, are practically unaffected by adverse weather and lighting conditions, and vendor will allow access to communications protocols. The result of the search was two nonintrusive systems: an active infrared detector and a passive acoustic detector. For ground truth, the research team selected a vehicle classifier that could use either inductive loop detectors or piezoelectric detectors, or both.

Besides determining the accuracy and reliability characteristics of new detection systems, TTI researchers also developed a system to interface between the detectors and the traffic signal controller cabinet. The primary element of the system was a 133 MHZ Pentium Industrial PC computer that would reside in the controller cabinet. This computer would run TTI-developed software that provided the appropriate logic to determine if an approaching truck met the criteria to extend the green signal to allow the truck to proceed through the intersection. The software programs developed by TTI consist of three main modules: the serial interface module, the large

vehicle identification module, and the green extension module. Due to differences in data elements utilized by each detector and differences in data protocols between systems, project staff developed a unique version of the serial interface module and the large vehicle identification module for each sensor system. Testing of both sensor accuracy and functionality of the TTI software occurred at two locations. Preliminary tests occurred at TTI's field test site in College Station, supplemented with a full scale and fully functional controller cabinet in TTI's TransLink® lab on the Texas A&M University campus. Final testing occurred in the Pharr district in Sullivan City.

Findings and conclusions of this research are based somewhat on a literature search, but primarily on field testing. This included detector testing and evaluation of TTI's software to connect to the controller cabinet and extend the green phase. The Schwartz Autosense II infrared is anticipated to maintain its accuracy in almost any weather and lighting conditions, although TTI did not test it in inclement weather. Its speed accuracy was not as consistent as desired for this application but software filtering would improve results. Its data variability as documented in its standard deviation was higher than the baseline system, and its speed bias of approximately 10 km/h (6 mph) can be adjusted through software. The classification accuracy of the Autosense II detector was adequate. In a sample of 160 vehicles, it only missed 3 percent and misclassified 7.5 percent. The detector's list price of $10,000 for one lane of coverage may be a constraint for some agencies.

The second nonintrusive detector included in this research was the IRD SmartSonic passive acoustic system. The TTI experience with this detector was limited due to early difficulties in properly mounting the detector and to equipment problems. Based on limited testing at the Pharr district field site, it appears to have some positive aspects but it needs continued enhancement for its classification accuracy to meet the needs of this research. Even its counts were low by a factor of 15 percent compared to the TCC. Its speed values were consistently higher than the TCC. For example, in a data set of approximately 2,000 non-trucks, its mean speed was 6 km/h (4 mph) faster than the TCC. Standard deviations were exactly the same for both systems at 12 km/h (7 mph). Cost of the acoustic detector system for two lanes was approximately $5,000, so its per-lane cost was significantly lower than the infrared sensor tested.

The other critical test requiring evaluation was the software and hardware components of the system designed to extend the green by connection to the Phase Hold terminals in the signal controller cabinet. Initial testing occurred in College Station at TTI's test site facility and in the TransLink® lab utilizing an Eagle EPAC 300 traffic controller. The field portions tested the serial interface and large vehicle identification modules using the Autosense II (AS2) and TCC detection systems. The Sonic sensor's module could not be tested due to delays in delivery and problems with the sensor. Once the lab tests of the green extension module were successful, the three modules were combined and tested in the field with both the AS2 and the TCC systems. In the absence of a cabinet for this portion of testing, staff tested the green extension module by observing the LEDs. These LEDs on system components used in the green extension module remained lit, indicating a signal was being sent for the duration of the green extension time. The green extension module extended the green time for every large vehicle detected traveling at a speed that required extension. The duration of the green extension time, based on the speed of the vehicle, worked flawlessly during field observations.

The final evaluation criterion utilized to determine the effectiveness of the system in Sullivan City was costs. Based on the volumes of trucks and non-trucks at this test site, it is anticipated that reduced delay savings would result in an annual savings of at least $1,300 for trucks and $2,600 for non-trucks. According to district personnel, the costs of pavement damage at intersections due to trucks stopping averages $30,000 per intersection. Using similar improvement percentages as for delay, the reduction in pavement damage per year per intersection due to the truck detection system would be approximately $1,000. At the test intersection in Sullivan City, the increased delay to side street traffic is negligible. Thus, the net anticipated total annual savings at this intersection would be approximately $5,000. Therefore, depending on the total life-cycle cost of the truck detection system selected and the number of trucks on the main street, there is anticipated to be an attractive benefit-cost relationship associated with the system. Also, this analysis ignored vehicle benefits, such as reduced brake and tire wear, that would also accrue.

1.0 INTRODUCTION AND METHODOLOGY

1.1 OVERVIEW

One of the most important transportation provisions of the North American Free Trade Agreement (NAFTA) that impacts the State of Texas allows trucks carrying goods between the United States and Mexico to travel freely into a border state of the other country. For Texas, this means that Mexican freight haulers will soon be able to drive Texas roadways as they deliver goods. While stimulating commerce between the U.S. and Mexico, NAFTA will also place greater volume and weight burdens on Texas highways. Similar effects of trucks are also felt throughout Texas in areas of high truck demand such as highly industrialized urban/suburban areas, near sand/gravel quarries, and near timber cutting and wood processing centers.

One research area that has the potential to improve both operations and safety and alleviate infrastructure and maintenance demands from both U.S. and Mexican trucking activities is improved signal operations in rural areas—especially at isolated intersections. Recent advances in sensing technologies and signalization enable more efficient and safe intersection control. In this application, video imaging, or other sensing technology with the capability of differentiating trucks in the traffic stream, and priority algorithms running on computer devices that work with existing controllers (or the use of advanced controllers that have their own computer capabilities) may be used as a system that guarantees green time (i.e., nonstop conditions) to trucks within some specified distance threshold of the intersection.

1.2 RESEARCH FOCUS

This research study entailed the implementation and analysis of sensing technologies at isolated intersections with high truck volumes. The study focused on the potential benefits of sensing trucks approaching such an intersection and a priority system that allows the truck to either not stop or to have time to stop comfortably. Avoiding hard stops by trucks at an intersection may reduce pavement damage and rutting, reduce maintenance costs, reduce air pollution, reduce accident rates, and reduce vehicular delays caused by additional stopping and frequent pavement overlays. Intersection safety would also be preserved, since truck drivers would not have to face the dilemma of trying to stop hard during a yellow signal indication, which is more closely linked to the stopping capabilities of automobiles, or running the light.

1.3 RESEARCH OBJECTIVES

The work plan for this study consisted of eight specific research objectives including: a literature search and review, an evaluation of available technologies, selection of equipment to test, purchasing the equipment, making any modifications to the equipment that are necessary, testing the prototype system, selecting the site and a field testing the prototype system in the Pharr District, and producing a final report on the project activities.

1.4 METHODOLOGY

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

1.4.1 Literature Search and Review

The researchers conducted a comprehensive literature search to identify publications and reports on various sensing technologies that are currently available for vehicle detection and signal prioritization. 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.

The systematic search of the above databases employed select key words and key word combinations. Some of the key words and key words combinations used in the search included: vehicle detection, non-intrusive technologies, non-intrusive vehicle detection, traffic data collection, detection technology, traffic monitoring, vehicle sensors, vehicle detectors, traffic sensors, traffic signals, traffic signal priority, traffic signals and transit, intersection control, signal preemption, signal green time, and vehicle prioritization.

Approximately 200 documents were identified as possible sources and were reviewed for relevance. The literature review is discussed in detail in chapter 2.

1.4.2 Evaluate Available Technologies

The research team evaluated detection systems that would be able to monitor approaching trucks at signalized intersections and track their speeds from as far as 183 m (600 ft) away from the stop bar. It was determined that the most desirable system would be capable of monitoring target vehicle speeds over the entire intersection approach length. This allowed the system to distinguish between trucks that are intending to continue straight through the intersection and trucks that are decelerating to make a turn. Two classes of sensors were deemed viable for this application—pavement sensors and roadside sensors. The pavement sensors consisted of piezoelectric axle sensors and inductive loop detectors (ILD). Roadside sensors that were initially deemed as most appropriate were video image detection systems (VIDS). This technology has increased in reliability, and cost is expected to decrease. However, other technologies were also evaluated.

1.4.3 Select Equipment to Test

The research budget included sufficient funds to purchase a monitoring system and ancillary equipment sufficient to instrument one approach to an isolated intersection. The primary intent for purchasing this equipment was to demonstrate system reliability in detecting trucks and providing sufficient green plus yellow time on the approach to clear trucks. A secondary objective was system expansion in the future to extend green time along a signalized arterial.

1.4.4 Purchase Equipment

After selection of a candidate type of monitoring system for purchase, the TTI research team developed general purchase specifications. The team determined that the monitoring system must be able to identify a truck and distinguish trucks from other vehicles at distances of up to approximately 183 m (600 ft) from the intersection. This distance was based on an approaching truck either clearing the intersection or arriving at a safe stop by using a deceleration rate that is acceptable for all weather and visibility conditions.

1.4.5 Modification of Selected Equipment

Once a system was purchased and received, the TTI research team evaluated necessary modifications to the system. The equipment selected did not include the originally anticipated VIDS, so this task changed from its original intent. This task consisted of writing software programs to interpret serial output of selected detectors and to communicate with the signal cabinet.

1.4.6 Test of Prototype

The TTI research team installed and tested the TTI program using its test site in College Station. Continued delays with some of the equipment forced some of the testing to occur in the Pharr district when equipment was installed to control an intersection there.

1.4.7 Site Selection and Field Test in Pharr District

With assistance from the project director and others in the Pharr District, the TTI research team selected a site to install the truck monitoring system. The site selected was on U.S. 83 in Sullivan City, which is located west of McAllen and Mission. Selection criteria for the isolated signalized intersection included: truck volume, approach speeds, controller equipment in place at the intersection, and the intersection's proximity to the district office.

2.0 LITERATURE REVIEW

2.1 OVERVIEW

Improved signal operations in rural areas, especially at isolated intersections, is one area for research that has the potential to improve operations and safety, and alleviate infrastructure and maintenance demands from both U.S. and Mexican trucking activities. One method to improve signal operations is to use new sensing technologies to facilitate more efficient and safer intersection control. In this application, video imaging (or other sensing technology with the capability of differentiating trucks in the traffic stream) and priority algorithms running on computer devices that work with existing controllers (or the use of advanced controllers that have their own computer capabilities) could possibly be used as a system that guarantees green time (ie., nonstop conditions) to trucks within some specified distance threshold of the intersection.

The potential benefits from a truck sensing and priority system are realized through trucks not having to stop (or having time to stop comfortably and safely) at isolated intersections. Avoiding hard truck stops may reduce pavement damage and rutting, lengthen pavement life, thereby, reducing maintenance costs and the delays caused by frequent pavement overlays. Intersection safety may also be preserved because truck drivers do not have to face the dilemma of trying to stop hard during a yellow signal indication (which more closely linked to the stopping capabilities of automobiles) or running a light.

2.2 VEHICLE PRIORITY AT SIGNALS

Providing selected vehicle priority at signals is not a new concept. Numerous cities implement a variety of strategies to provide priorities to buses and/or streetcars. These strategies have met varying degrees of success. In a study of implementation of bus priorities at isolated intersections, Vincent, Cooper, and Wood (*1*) described various forms of priorities including:

- **priority extension facility** whereby the selected priority vehicle (in this study a bus) can maintain a green signal, used on its own or with other facilities,
- **priority call facility** which regains the green for buses; used alone or with other facilities, and
- **non-priority facilities** which recompense the non-priority stage after its curtailment by a priority call.

These forms of priorities, which were called selective detection priorities in later studies by Cooper (*2*,*3*), allow traffic signal operations to be influenced by approaching buses. A computer simulation model was used to study junctions with three traffic stages or with two traffic stages and a pedestrian stage. A range of bus and other vehicle flows was simulated and findings revealed that although buses could be given substantial benefits, other vehicle travel times may be increased. Therefore, a tradeoff of benefits must be considered when implementing such priorities.

Sunkari, et. al., (*4*) concluded that a model estimating the impacts of providing priority to buses at signalized intersections is a helpful tool to traffic engineers. The model, which encourages the increased use of bus priority strategies and measures, may lead to better bus operations and the bus as a viable alternative to the car. This, in turn, could result in the reduction of vehicle-miles of travel, energy conservation, and a reduction in mobile source emissions.

European cities have led in the deployment of automatic vehicle location/control, and traffic signal preemption systems. Baker, et. al., (*5*) documents the lessons learned by European implementation. The United Kingdom developed and tested one such system, which is known as Microprocessor Optimised Vehicle Actuation (MOVA). MOVA is a strategy that may provide a means of reducing delay at isolated signal intersections by utilizing the key principles of vehicle-actuated control with microprocessor technology. Vincent and Pierce (*6*) found that conventional gap-seeking, D-system vehicle-actuated controls are very effective; however, they do have the following two limitations:

- Inefficiently extending green times, when traffic is flowing at considerably less than full saturation rate, especially on multilane approaches, and
- Inappropriately setting maximum green times that adversely affect delays.

Both of these difficulties are overcome by the self-optimizing features of MOVA. MOVA uses buried inductive loops for detectors and an on-line microprocessor as a controller. Although this system may not be compatible with U.S. traffic signal controllers, the same type of system should be included in at least the preliminary investigation.

2.3 DETECTOR TYPES

As previously stated, one requirement to successfully implement signal prioritization at isolated intersections is sensing and detector technology that has the ability to detect vehicles and to differentiate trucks from the rest of the traffic stream. The majority of vehicle detection today is accomplished using inductive loop detectors. Brief descriptions of some of the existing detection devices and the most promising new innovations are provided below.

2.3.1 Inductive Loop Detectors

The inductive loop detector is composed of 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. Electrical induction in a traffic signal system is comprised of a detector unit that passes a current through stranded loop wire, thereby creating an electromagnetic field around the wire. Moving a conductive metal object, such as a vehicle, through this electromagnetic field disturbs the 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, introduced in the 1960s, continues today as the most commonly used form of detector, even though its weaknesses are widely recognized.

Traffic control costs and delay costs for loop installations may make loops less competitive than their newer detector counterparts. Another disadvantage is the expense of relocating or repairing loops after installation, which requires extensive traffic control and results in congestion and motorist delay (*7*). Detector "cross-talk" and increased pavement stress are also disadvantages of inductive loop detector systems. There are also several conditions that may affect inductive loop detector operations, these include: high voltage power lines under the pavement, a pavement subsurface with a high iron content, and unstable pavement conditions. Modern detection equipment can overcome the first two conditions, but changing or unstable pavement conditions result in increased maintenance costs (*8*). One advantage of inductive loop detection systems is their ability to operate in all weather and lighting conditions.

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. One study that interviewed 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 five 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 (*9*). Such programs are costly, but maintaining a low failure rate requires them.

Bikowitz (*10*) et al., 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 that 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.

2.3.2 Microloop Detection Systems

A microloop detection system is a passive sensing system 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 of 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 (*8*).

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 *(9)*.

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 (*12*).

2.3.5 Piezoelectric Sensors

Piezoelectric sensors are a film or cable 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 (*13*). 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.

One advantage of piezoelectric sensors is their ability to be utilized as WIM detectors, but the sensors used for WIM applications are more accurate and more expensive than piezos used for classification. Piezoelectric sensors can serve as axle sensors, so they can be used to distinguish between vehicle types (*13*, *14*). 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. Piezoelectric sensors have become more extensively used in the United States in recent years.

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 (*15*).

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 *(9)*. 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 to collect speed data. The operating frequency of the signal is normally in the K-band (24 gHz) or the X-band (10 gHz)(*16*).

Radar detectors, commercially available for years, use a pulsed energy beam. The beam, which is either frequency-modulated or pulse-modulated, detects vehicles by 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. Current radar sensors for freeway applications have the ability to detect vehicles, produce traffic counts, and to 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 their inability to detect a stopped vehicle and to measure occupancy (*9*). In the past radar systems have been vulnerable to vandalism (*17*). 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. *(9)* 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 (*9*).

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 (*9*).

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 (*18*). 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 (*16*). 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 (*9*).

2.3.10 Active Infrared Detection Systems

Active infrared sensors integrate lasers, optics, and optical detectors into active laser radars (ladars) for sensing vehicles passing through the detection area. These detectors create an image of a moving vehicle through the use of a nanosecond-pulse semiconductor laser ranging system. The infrared detection system is aimed such that the beam strikes and returns from the pavement until a vehicle passes through the detection zone directly underneath the detector. It measures the return time of the reflected laser power, converting this time to distance. The detection system's computer generates images based entirely on the range data and a high scan rate which, in one example case, is 720 scans per second.

Preliminary testing by public agencies indicates very promising results for monitoring vehicle speeds and classifications. Active infrared systems appear to operate acceptably 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 detection 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 (*16*).

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. 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 (*19*).

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 (*19*). 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 (*19*). 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 processing 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 processing software. Real-time detection also became available with these technological advances (*20*, *21*). 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 (*22*). 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 processing 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 loops systems and are intended to replace inductive loops in areas where a large number of loops are employed. Most of the video image processing 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 (*23*).

Closed loop tracking systems, the second generation of video image processing 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 (*23*).

Data association tracking systems, commonly used in satellite surveillance systems, are the third generation of video image processing 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 testing results for 10 commercial or prototype video image processing systems available in the United States (*24*). 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 AutoScope.

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 (*24*). 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. 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 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 provide 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 (*25*, *12*, *26*).

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 (*26*). The performance results for each of the eight technologies tested in regards to the intersection site 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 the intersection testing location 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 (*26*).

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 Eltec models tended to overcount vehicles at the intersection height (*26*).

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 is easy to mount and calibrate. Repeatability was good. One device was observed undercounting vehicles during snowfall, however this miscounting may have been the result of vehicles traveling outside of the IR 224's detection zone. The results of this device during an optimal 24-hour count period at the intersection (within 2 percent of baseline data) were the best overall results obtained from any detector at the intersection site (*26*).

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 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 (*26*).

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 232E/231E Probe. The passive magnetic devices were not tested at the intersection location (*26*).

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 analyze 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 (*26*).

The Peek PODD requires that mounting be either overhead or slightly to the side of and facing oncoming traffic. Poor aiming of the device may have lead to undercounting or overcounting. The PODD was not able to collect good data for the intersection site. The Whelen TDN-30 also requires that mounting be either overhead or slightly to the side of and facing oncoming traffic. The primary role of the TDN-30 is to collect speed data and the device was not able to collect meaningful data at the intersection site (*26*).

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. The RTMS was not tested at the intersection site (*26*).

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. Researchers found that both SmartSonic devices overcounted vehicles during testing at the intersection site (*26*).

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 returns 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 (*26*).

The TC-30, which may be mounted either overhead or sidefire, was found to have 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 found to overcount at the intersection site. This was surmised to be the result of double counting. The two pulse ultrasonic devices interfered with one another when mounted next to each other (*26*).

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 Video Trak-900, the Image Sensing Systems Autoscope 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 (*26*).

The Peek Transyt Video Trak-900 is capable of monitoring input from up to four cameras. When the device was installed at 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 Trak-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 the intersection test site. Light changes during transition periods also resulted in undercounting by the Autoscope (*26*).

Researchers found that the Eliop Trafico EVA 2000 detection system was capable of very accurate freeway counts; however, the system 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 did not test the TraffiCam-S at the intersection site (*26*).

2.4.3 Hughes Aircraft Company Field Performance Tests

Hughes Aircraft Company conducted an extensive test of non-intrusive sensors for the FHWA. The objectives of the study, *Detection Technology for IVHS*, (*27*) 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 video image detection systems (VIDS), infrared VIDS, acoustic array, SPVD magnetometer, and inductive loops (*27*).

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 microwave Doppler, microwave true presence, visible VIP, SPVD magnetometer, and inductive loop technologies performed well for low volume counts. The microwave Doppler, microwave true presence, visible VIP, and inductive loop performed well for high volume counts. The microwave Doppler was the best performing technology for low volume speed and for high volume speed. The microwave Doppler, microwave true presence, SPVD magnetometer, and inductive loop technologies performed best in inclement weather.

2.5 DILEMMA ZONE PROTECTION

The term dilemma zone refers to either a physical segment of the intersection approach, or it can be defined in terms of the decision-making process. The "physical segment" refers to a physical length of the approach in which a driver cannot go through the intersection or stop legally. The "decision-making" definition refers to the area where the probability of drivers attempting to stop is between 10 and 90 percent (*28*). In both early and current research on dilemma zones there is some disagreement as to the location of the dilemma zone boundaries. Some of this disparity can be explained by differences in driver/vehicle populations at the various test sites. In more recent studies, Bonneson et al. *(29, 30)* noted a trend toward increased length of dilemma zone boundaries compared to older study findings. They suggested the reason for the increase is the results of a trend toward decreasing driver respect for the change interval.

In early dilemma zone analyses, Parsonson et al. *(28)* examined and summarized existing research on the probability of stopping from various speeds *(31, 32, 33)*. Comparison of data collected by Zegeer of the Kentucky Department of Transportation *(34)* revealed that his dilemma zones (10 and 90 percent probabilities of stopping) were 28 percent to 38 percent longer than those measured by Parsonson et al. *(28)* for speeds of 72 km/h to 80 km/h (45 mph to 50 mph). Since Zegeer's data were collected under closely controlled conditions, many practitioners have used his data.

Using passage time as a parameter, Zegeer found that five seconds was sufficient for vehicles to travel from the initial upstream detector to the intersection for speeds below 95 km/h (60 mph). Other methods used before these analyses involved kinematic analyses of either stopping or clearing the stop bar. Some early investigators used AASHTO (then AASHO) minimum stopping sight distances, while others used a one-second driver reaction time and an emergency stop on dry pavement (*35*).

One of the detector-controller design scenarios that looked very promising to early investigators used a green extension system, apparently similar to that used today. One example used a 21 m (70 ft) loop detector at the stop bar for normal detector output supplemented by an extended call detector five seconds before the stop bar. Zegeer *(34)* reported on the effectiveness of five locations in Kentucky, concluding that there was an overall accident reduction of approximately 50 percent compared to previously used detection scenarios. Another parameter measured by Zegeer in dilemma zone studies was traffic conflicts *(36)*. In studies conducted before and after the installation of green-phase extension systems (GES), he used the following six types of conflicts: red light runs, abrupt stops, swerve to avoid collision, vehicle skidded, acceleration through yellow, and brakes applied before passing through the intersection. Zegeer's findings included reductions in conflicts at two test sites with the use of GES. Mean values of conflict rates reduced from 4.34 to 2.64 conflicts per 15-minute interval at one site and from 4.22 to 0.66 conflicts at another site.

In a recent *ITE Journal* article entitled, "Traffic Detector Designs for Isolated Intersections," Bonneson and McCoy *(29)* provide some insights based on their recent research on detector design *(30)*. They stated that the overall objective in properly designing detection at actuated high-speed approaches is to minimize delay without compromising safety. This is typically accomplished by proper coordination of detector size and location with the various timing features of the detector unit and controller. The authors discuss dilemma zone protection and describe it as the prevention of phase termination while a vehicle is in the dilemma zone. This protection may be achieved by strategically locating detectors on the intersection approach and adjusting the detector unit settings such that a vehicle can "hold" the green while it travels through the dilemma zone. As vehicles approach the dilemma zone, drivers face a decision upon onset of yellow to either stop or proceed through the intersection. Intuition suggests a correlation between the number of vehicular crashes (typically rear-end) and frequency of "max-out." This is primarily due to a leading vehicle that attempts to stop followed by a vehicle in the same lane that attempts to proceed. The authors promote the idea of dilemma zone protection through proper design of advance detectors.

Bonneson and McCoy discuss recommended detector designs for both urban and rural actuated signalized intersections. Advance detector design is determined by the range of speeds on the approach. Each advance loop has its own design speed, with the highest design speed for the detector farthest from the stop bar. Each subsequent detector has a design speed of approximately 16 km/h (10 mph) less than the one just upstream. One indicator of design performance is the maximum allowable headway (MAH) produced by a particular detector design. The MAH represents the maximum time headway that can occur between successive calls to the controller such that the green is extended in spite of demand on a conflicting movement. There is no set MAH that is best for all detector designs due to the many possible variables. In general, shorter MAHs reduce the frequency of max-out and delay to waiting traffic. The authors suggest using the *Manual of Traffic Detector Design* (*37*) for determining a design's MAH.

Woods and Koniki, in a final report entitled, *Optimizing Detector Placement for High Speed Isolated Signalized Intersections Using Vehicular Delay as the Criterion*, *(38)* noted a negative aspect of providing dilemma zone protection. On high-speed approaches to an isolated intersection, providing dilemma zone protection may result in sluggish operations and possibly higher delays. A trade-off analysis of detector placement is essential for optimization of dilemma zone protection and reducing delays. Woods and Koniki utilized the TEXAS Model (Version 3.2) to determine optimal detector placement strategies on high-speed isolated intersections. Traffic volumes varied between 200 vehicles per hour per approach to 800 vehicles per hour per approach. Mean speeds of 90 km/h (55 mph), 70 km/h (45 mph), and 55 km/h (35 mph) were simulated. Detector placements were developed for both the mean and 85th percentile speeds.

The authors used a regression analysis on delays and cycle lengths to show that a strong linear relationship exists between them. This analysis varied detector layouts to develop this relationship. At low approach volumes, there was no effect of mean and 85th percentile speeds on delays, whereas at higher approach volumes, 85th percentile speeds resulted in higher delays.

2.6 TRAFFIC CONTROL AT HIGH-SPEED INTERSECTIONS

In a study by Parsonson, reported in a NCHRP Synthesis entitled, *Signal Timing Improvement Practices* (*39*), information is provided on traffic signal phase change interval practice in various states. He found that at least half of the states follow the "permissive yellow rule" that permits vehicles to enter an intersection on a yellow signal and to be in the intersection when the signal changes to red. Parsonson noted that the *Manual of Uniform Traffic Control Devices* (MUTCD) *(40)* provides the following guidance regarding change intervals, "Yellow vehicle change intervals should have a range of approximately 3 to 6 seconds. Generally, the longer intervals are appropriate for higher approach speeds."

Parsonson conducted a survey regarding yellow time and approach speed; Table 2-1 provides the results. Findings of the study included: 1) there is a need for uniform timing practices and procedures, 2) there is a need for field observations prior to setting signal timing, and 3) there is a tendency for computer program generated cycles to be too short.

Table 2-1. Change Intervals Used by Various Jurisdictions

City, County, or State	Speed km/h (mph)	Yellow Time (seconds)
New York State	88.5 (55)	5.0
	96.5 (60)	5.4
Iowa DOT	>64.4 (40)	5
Montgomery County, Maryland	>72.4 (45)	5
Lakewood, Colorado	88.5 (55)	5.5

In a study entitled, "Traffic Control and Accidents at Rural High-Speed Intersections," *(41)* Agent examined the effect of traffic control on accidents at high-speed rural intersections. The objectives of this study were:

- Determine the types of traffic control measures used at rural high-speed intersections,
- Establish the type of accidents that occur at rural high-speed intersections,
- Discover the factors that contribute to these accidents, and
- Recommend the traffic control measures that could most effectively decrease potential accidents.

Agent conducted the study by using a sample of rural high-speed intersections in Kentucky. He evaluated accident records, using the following site specific factors as variables: geometry, traffic control measures, speed, sight distance, channelization, pavement markings, and intersection type. Agent found that providing the driver adequate warning of the intersection, providing proper change intervals, and maximizing visibility of the signal heads were important to minimizing the accident risk at high-speed rural intersections. He also noted that a red clearance interval should always be provided for both roadways.

Agent and Pigman (*42*), in their study entitled, *Evaluation of Change Interval Treatments for Traffic Signals at High-Speed Intersections*, found that a large number of traffic accidents at signalized intersections on high-speed roadways occur during or just after the change interval. The green extension system is extensively used in Kentucky as a way of alleviating the problem related to the dilemma zone. This study evaluated both the green extension system and an advanced warning flasher system. The study evaluated how these systems could be used in diminishing problems associated with dilemma zones at signalized intersections, with a specific focus on high-speed roadways.

2.7 ALL RED CLEARANCE INTERVALS

The all red clearance interval proposed by Agent in his study of rural high-speed intersection study has been debated by traffic engineers as a safety measure. A number of studies on the subject as it relates to intersection safety have been conducted. These studies include research by Newby (*43*), the ITE Technical Council Committee 4A-16 (*44*), Benioff, et al. *(45)*, and Roper, et al. *(46)*.

The Newby study documented four years of research, two years before and two years after, on 12 intersection sites in England. The study showed that there was a definite decrease in accidents. This decrease was attributed to the introduction of all red clearance intervals (*43*).

Benioff, et al. conducted a comprehensive study which examined all red clearance intervals at 45 sites. This research, which used accident rates as the primary measure of safety, found that the total accident rate decreased mainly to a reduction of the right-angle accident rate (*45*). Research by Benioff, et al. in 1980 concluded that when an intersection has a right-angle accident rate greater than 0.8 right-angle accidents per million entering vehicles should consider implementing all red clearance interval.

A report by the ITE Technical Council Committee 4A-16 in 1985 found in the Hamilton-Wentworh Regional Municipality in Ontario, Canada, a 21 percent reduction in right-angle accidents was recorded during the first year after the implementation of all red clearance intervals (*44*).

It should be noted that Roper, et al. observed that none of these previous studies used a comparison group to measure the all red clearance interval's success relative to intersections without the all red clearance interval (*46*). The study by Roper, et al. examined 50 intersections in Indiana, 25 intersections that were "treated" with the all red clearance interval and 25 comparison or control intersections. The study concluded that there was no significant long-term decrease in accidents by the use of the all red clearance interval. This was attributed to the possibility of the driver adjusting to the all red clearance as it becomes more common. Roper surmised that drivers may be "extending" the yellow clearance into the all red interval (*46*).

3.0 TECHNOLOGY EVALUATION

3.1 INTRODUCTION

The original equipment purchase plan proposed buying video image detection system (VIDS) equipment to detect trucks and meet other project objectives. However, one early finding was that no video image system equipment could classify vehicles in all lighting conditions. VIDS equipment typically classifies vehicles in daylight based on length, but at night this equipment reverts to detection of headlights only, and not length. VIDS cannot distinguish truck headlights from car headlights, and thus cannot classify vehicles at night. One solution was found to this VIDS problem but it required street lighting for the entire approach distance of approximately 152 m (500 ft). Thus, the revised work plan expanded the purchasing and evaluation process to include other technologies that might have the potential to accurately detect trucks and generate real-time vehicle-specific data via the serial port. Once purchased, the equipment would undergo modification and testing, similar to what had been preplanned for VIDS.

The original work plan also changed. Initially, TTI would have tested detection equipment first in the lab, then at a field location at an intersection in the Bryan/College Station area. The field portion required testing in an "off-line" mode initially and perhaps testing on-line at the same intersection if successful. Equipment delays and lack of approval by the selected jurisdiction, changed the test plan. TTI personnel used an alternate field test plan to utilize their new "test bed" on State Highway 6 in College Station to determine detection accuracy. The plan also included development of algorithms to "interpret" signals from the detectors to 1) compare with ground truth data and 2) interface with a traffic signal controller cabinet located in the TransLink® Lab for initial testing of the algorithms. The purpose of the algorithms was to send an electrical signal to the controller cabinet that activated the *phase hold* for a preset number of seconds. Upon completion of both test elements, researchers combined detection and sending the signal for the IR detector and the vehicle classifier. There were numerous delays regarding the acoustic system so project staff were forced to begin its algorithm testing after moving the detectors to the Pharr District. The final phase of tests for all systems occurred in the Pharr District, first off-line then on-line.

3.2 EVALUATION OF VIDS TECHNOLOGY

At the outset of this research, it appeared that the technology of choice to accomplish study objectives was VIDS. As the process of evaluation continued, however, it became evident that VIDS would not be able to meet the conditions stipulated by the sponsor of being able to classify vehicles in all lighting conditions *without* street lighting along a substantial length on the test intersection approach. Even though a test intersection could be found that had the desired characteristics, there would likely be many other intersections without the necessary street lighting. The decision process is still included below because continued improvements in VIDS may make it a viable system in the future.

Table 3-1 provides a partial list of video image system capabilities considered necessary for meeting project objectives. Project team staff selected the six video image systems based on those that TTI had tested, those that TxDOT was considering for purchase, and those that were initially thought to be viable products for accurately monitoring traffic. Of these six devices, some were "trip-wire" systems and others are "tracking" systems. For this research, tracking was considered essential, reducing the number of viable systems to three, the Peek *VideoTrak™ 900*, the Condition Monitoring Systems *Mobilizer*, and the system by InVision (Intelligent Vision Systems). Real-time serial data recovery was also essential; however, being available in a VME (versa module Europe) chassis is not absolutely necessary. The system design for this project could have taken advantage of Peek's VME design but utilization of a stand-alone computer was also acceptable. Speed accuracy was essential, as well as vehicle-specific speeds and being able to generate an alarm based on preset speed criteria. Vehicle classification based on length (as opposed to axle spacings) was considered sufficient for this project. Camera "hand-off" refers to a series of at least two cameras that allow continuous monitoring of each truck on the same approach. Camera "A" would track a truck for approximately half the approach distance, then hand off to camera "B," perhaps based on dimensions, speed, and time stamp. Orientation of the camera may not be critical, depending upon intersection geometrics.

Other items besides those listed in Table 3-1 could be added to the list of performance criteria for identifying viable video image systems, although not all were considered critical in this project. These include incident detection, queue length, and turning movement counts. A critical item to be considered is the communication protocols and whether compatibility exists between various traffic control elements.

Of the three tracking systems, TTI had conducted limited testing on two, the CMS *Mobilizer* and InVision. The CMS was a promising system, but progress on final testing and system modification was proceeding very slowly. One reason was the company was small and at that time they were relying upon a few selected agencies to beta test their system and solve problems. InVision provided one of its units for testing at the Texas A&M University Riverside campus under the direction of TTI staff. The unit had some very positive features, but the test was not comprehensive and was not conducted in a "real-world" environment. Its desirable results included accurate speed results when mounted on a high-mast light support, demonstrating that its swing-sway compensation functioned properly. However, project staff were not confident that InVision would have a viable product ready soon enough for this research.

Based on preliminary information from the manufacturer, the Peek VideoTrak™ 900 system appeared to be best for this research. Researchers were encouraged to learn that it could be forced to remain in the daylight mode after dark such that it would monitor vehicle length and not headlights. Still other aspects of the Peek appealed to researchers. Peek claimed an observed

Table 3-1. Video Image Processing System Matrix

System Capability	Autoscope 2004	CMS Mobilizer	InVision	Odetics Vantage	Peek VideoTrak 900	Visitech
Tracking	No	Yes	Yes	No	Yes	No
Real time serial data recovery	No[a]	Yes	?	Yes	Yes	No
VME Chassis	No	No[a]	?	No	Yes	No
Vehicle classification-length	Yes	Yes	Yes	No[a]	Yes	Yes
Vehicle classification-axles	No	No	No	No	No	No
Speed accuracy acceptable	No	Yes	Yes	No	Yes	No
Speed alarm	No	?	?	No	No[b]	?
Speed is vehicle specific	Yes	No[a]	?	No	No[b]	?
Camera "hand-off"	No	No[a]	?	No	No	No
Any camera orientation	Yes	Yes	Yes	No[c]	Yes	?

[a] Expected to have within the next 6 to 12 months.
[b] Next generation of Peek software is anticipated to have this capability; time frame is first quarter 1996.
[c] No "side fire" capability.

speed accuracy on the VT 900 of plus-or-minus 3 km/h (2 mph) at prevailing speeds of 97 km/h (60 mph), making it viable for this research. The cost of a four-camera unit was $18,000 and cameras cost approximately $2,000 each, so it was within the budgeted allocation for equipment. Of course, one very positive feature of video technology is its flexibility. Once cameras are installed, the user can move and manipulate sensor locations to optimize performance. Again, for intersections without street lighting along the entire approach length, VIDS was not a viable option. There were also weather conditions that compromise the accuracy of video detection systems. Therefore, based on the information available at the time the decision was made, VIDS systems were not the most appropriate choice for this project.

3.3 EVALUATION OF NON-VIDS TECHNOLOGIES

3.3.1 Literature Search

Until the change in the equipment purchase plan, only VIDS had been evaluated, with the exception of ground truthing systems that utilize inductive loops and/or piezoelectric sensors. One very crucial criterion for selecting the detection system was that it be able to detect trucks in all weather and lighting conditions. It must also communicate through a serial port to facilitate the signal to the controller cabinet extending the green indication on the test approach. Table 3-2 summarizes the technologies that have been investigated and some of their characteristics, based on recent research by the Minnesota Guidestar program *(47)*. Besides video and magnetic devices, these technologies include: active infrared, passive infrared, radar, doppler microwave, and passive acoustic. Of these, the ones that appeared to hold the most promise based on telephone interviews and the literature, and which are deemed worthy of further consideration are: pavement detection systems, passive acoustic, and active infrared. The text that follows provides results of the survey and the basis of the decisions regarding which technology to use for detection of trucks.

3.3.2 Telephone Survey

Project staff made several telephone calls to equipment vendors to discuss project needs and to discuss how specific equipment might fit those needs. Usually one phone call was required to schedule the actual conference call to get all the appropriate people to talk to project staff. Figure 3-1 is a general list of questions followed during this interview process. A requirement was that selected vendors must also be willing to relinquish information that might otherwise be considered proprietary. For TTI to be able to use each detection device for this project, output data format and possibly other information must be available. There should also be a technical contact available to TTI during the modification process. Based on the available information, the following three technologies seemed viable for this research: radar, acoustic, and active infrared.

3.3.2.1 Radar

Electronic Integrated Systems Inc. of Canada distributes a radar detection system called Remote Traffic Microwave Sensor (RTMS). As Table 3-2 indicates, it generates speed and classification data, even though it only classifies in two vehicle types, cars and larger vehicles. Recent testing by the Minnesota Guidestar program indicated that this system is very promising based on a large data set. However, the conversation with a senior engineer and the vice-president of marketing revealed some serious limitations that rendered it unviable for this project. It generates output via a serial port; however, it averages vehicle parameters over a minimum 10-second period. If the user could have shortened this period to monitor only one vehicle, it might have been acceptable.

3.3.2.2 Acoustic

International Road Dynamics (IRD) of Saskatoon, Saskatchewan, Canada, recently purchased the SmartSonic acoustic detector from AT&T and is continuing its development for transportation applications. The sensor began as a military application and was modified for its current use. According to IRD claims, its speed accuracy was plus-or-minus 8 to 10 km/h (5 to 6 mph) at highway speeds as compared to loops. It did not initially have classification software but IRD predicted that the modification would be finished by August 15, 1996. Its power requirements are a low 5 to 6 watts, allowing the use of solar panels if needed. The August 15, 1996 system modification would also allow serial port data capture. The cost of each sensor array was $1,450 per unit, with one required per lane per detection location. This system also required a controller card at a cost of $800, with each card accommodating up to four sensors. Project 2972 required two of these sensors to detect truck speeds at 122 m to 152 m (400 to 500 ft) from the intersection. According to IRD, the distance between sensor and cabinet can be up to 610 m (2,000 ft) because it operates on a 24V power source. Mounting requirements are a minimum of 6.1 m (20 ft) overhead and 7.6 m (25 ft) horizontal distance from the travel lane. It can be mounted in a side-fire or parallel orientation.

IRD manufactured the current model, the SmartSonic Traffic Surveillance System (TSS-1), which detected vehicles and measured traffic flow on highways using acoustic sensors. Three primary hardware components made up the SmartSonic TSS-1: the sensor, interconnecting cables, and the controller. As the sensor detected vehicles and assessed them, it sent the information to a traffic controller, or control center, where the information was saved.

Effectively, the goal of the SmartSonic TSS-1 was to provide a reliable, all-weather, and cost effective alternative to magnetic induction loops. IRD claimed that there is no interference at all due to inclement weather, other than very dense fog. The TSS-1 did not require vehicular contact and could be mounted on bridges, overpasses, light poles, and sign fixtures. This allowed for easy installation and utilized a variety of suitable mounting structures already in existence. The lightweight structure and small size of the SmartSonic TSS-1 also simplified installation. Furthermore, it complied with freeway and arterial surveillance requirements.

Table 3-2. 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
Active Infrared	Santa Fe Technologies/ Titan -- SmartLOOK	volume, presence, classification, acceleration, speed	$8,000	PC
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	MicrowaveSensors,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 Autoscope 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 *(47)*

[b] Price is estimated.

SYSTEM: ____

TECHNOLOGY: ____

CONTACT NAME: ____

Project overview: Detect trucks at high speed and generate accurate speeds at 400 to 500 feet away from an isolated signalized intersection.

1. Does the detector output include speed and classification?
2. What is the accuracy?
3. Does it generate real-time output via serial port?
4. What is the cost of -- 1 unit ______; 2 - 10 units ________; over 10 _________
5. Field computer required?
6. How is it mounted? Overhead? Sidefire?
7. What effect does weather have on results?
8. What effect does lighting have on results?
9. Agencies who are currently using this device and contact names:
10. If we need more information who to call:
11. Other:

Figure 3-1. Equipment Survey

Table 3-3. Detection Device Summary Based on Interviews

Parameter	Peek VideoTrak 900	IRD SmartSonic	Schwartz Autosense II	IRD Classifier TCC 540
Speed accuracy	±2mph at 60mph	±7mph at 60mph	±3mph at 60mph	±1mph at 60mph
Classification accuracy	± 5% (day)	??	100%	78.8 - 96.2%
Real-time data output	Poll by computer	by 8/96	Yes	Yes
Serial port	Yes	by 8/96	Yes	Yes
Cost	$22,000	$1,500	$10,000	$2,000
Mounting requirement	Existing pole	Existing pole	Mast arm	Roadside
Weather restrictions	Fog, heavy rain	heavy rain	heavy fog, dust	none
Lighting restrictions	Daylight only	none	none	none
Track record	6 months	Few years	Few years	Many years
Access to code	Yes	Yes	Yes	Yes?

The SmartSonic TSS-1 operates on the basis that vehicles emit sound energy due to internal vehicle sources and the interaction of the road with a vehicle's tires. Each sensor contains a microphone array which continuously listens for sound energy. A programmable digital signal processor (DSP) processes the microwave signals. These signals create a single detection zone for each sensor. The typical detection zone dimensions for the TSS-1 are similar to that of an inductive loop that is 1.8 m by 1.8 m (6 ft by 6 ft) in nominal size. The actual shape and size of the detection zone varies depending on the installation geometry of each individual sensor.

Sound energy increases as a vehicle enters the detection zone. The sensor acknowledges this increase by generating a vehicle presence signal, which is sent to the traffic controller. The sound energy decreases below the detection threshold as the vehicle leaves the detection zone, causing the vehicle presence signal to become inactive. Sounds that do not pass through the detection zone are not recognized by the sensor.

Up to four sensors can be connected to a traffic controller for processing. The controller contains a programmable microprocessor which processes the vehicle detection and computes traffic flow measurements at selectable intervals. Vehicles could be detected at all speeds and even when they were stopped. The microprocessor acclimates to varying pavement conditions due to weather and pavement types. The traffic flow measurements that can be evaluated include vehicle volume, lane occupancy, average headway, and average speed of all the vehicles detected during a specified time period.

3.3.2.3 Active Infrared

Schwartz Electro-Optical, Inc. in Orlando, Florida, which got its start developing military applications, sells two active infrared (IR) products for traffic detection: Autosense I and Autosense II. Both active laser detectors monitor a small area at the detection site, requiring one device per lane per location. The Autosense I system monitors a slice down the centerline of a lane. Schwartz claims that its height accuracy is adequate for traffic speeds well above 160 km/h (100 mph). The reason they developed Autosense II was that vehicles could miss detection by the first version, especially if vehicles were changing lanes as in high weave areas on multilane roadways. Autosense II uses two beams at 2 degrees apart, and it can effectively create a three-dimensional image measurement. Figure 3-2 illustrates the infrared beam configuration. These two devices can differentiate between 12 different classifications, although in its current version it does not classify based on axles or axle spacing. The vehicle classes are shown in Table 3-4 . Based on this classification scheme, it becomes obvious that the detector can detect when a vehicle is connected (e.g. tractor and trailer). Figure 3-3 indicates features of an articulated vehicle as detected by the Autosense II infrared detector. Some locations where the Autosense detectors have been or will be installed are: Route 91 in California, Highway 407 in Toronto, and Highway 470 in Denver. The detectors will be used for electronic toll collection in Toronto.

Table 3-4. Vehicle Classifications by Autosense II

Vehicle Class	Description
0	Unknown
1	Motorcycle
2	Motorcycle with trailer
3	Passenger car
4	Passenger car with trailer
5	Pickup/van/sport utility vehicle
6	Class 5 with trailer
7	Single unit truck/bus
8	Class 7 with trailer
9	Tractor with one trailer
10	Tractor with two trailers
11	Tractor with three trailers

The vendor claimed that the accuracy of Autosense II is over 90 percent on classification and 99 plus percent on detection. They claim to have captured speed data with accuracy within 2 km/h (1 mph) for Autosense I and 5 km/h (3 mph) for Autosense II. Another State Department of Transportation conducted detection tests with 99.6 percent accuracy on detections. Company spokesmen stated that a benefit of IR is that it does not have privacy issues associated with it like video imaging systems do. Their systems do not have problems at all in rain and lightning or with any combination of lighting conditions. They do not have snow data, but Hughes Aircraft is buying 350 of them for the Toronto Highway 407 project, so they obviously have confidence in them in an area that has snow. For temperature extremes, the Autosense detectors are built to withstand -40° C to + 70° C. Full coverage requires one detector per lane.

The two Autosense units generate vehicle-specific speed and class data that are available via an RS-232 port. Autosense I can be installed as a side-fire device, but Autosense II has not

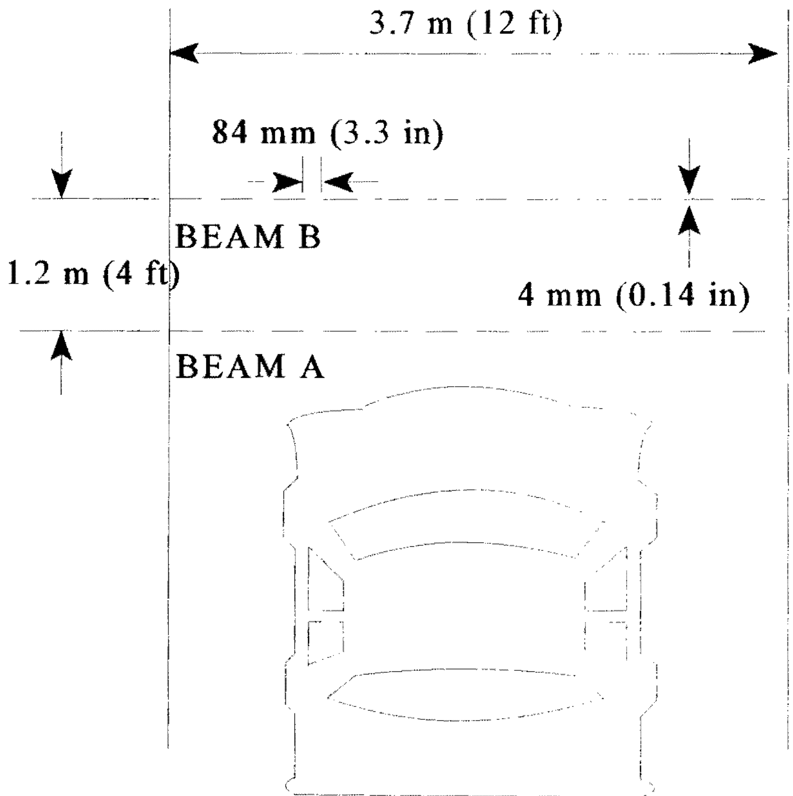
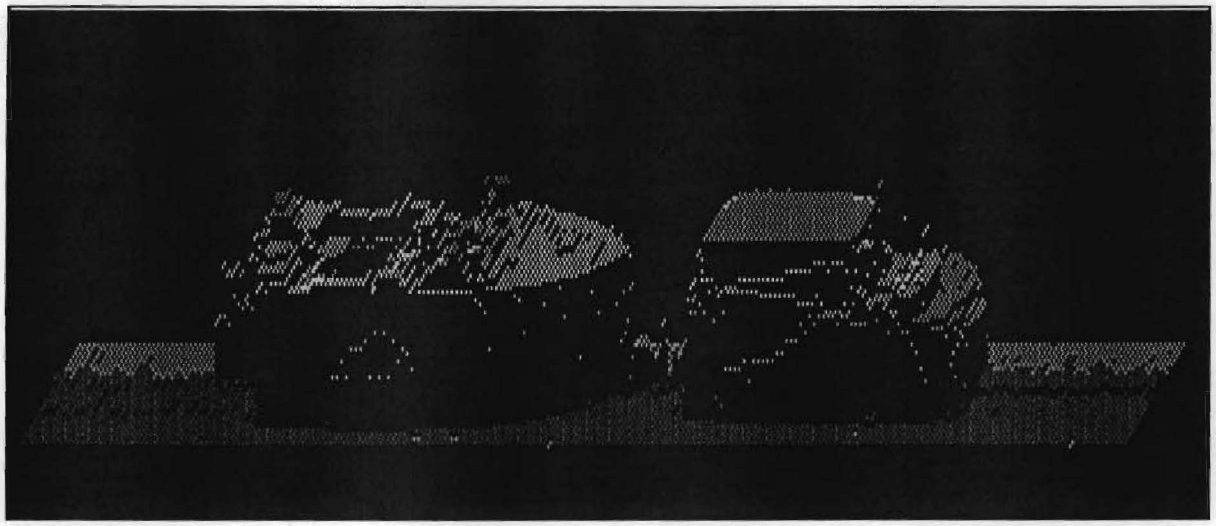


Figure 3-2. Infrared Beam Configuration



Source: Schwartz Electro-Optic, Inc.

Figure 3-3. Schwartz Autosense II Detector Image

undergone full testing in the sidefire mode. Mounting Autosense II as high as 15.2 m (50 ft) makes the detection width approximately one lane wide. The system calibrates itself, and it must be mounted at the point where speeds and classifications are desired. It cannot be simply mounted on a pole at the intersection like a video system camera can be. The machine can be set to store data internally with periodic retrieval or data can be downloaded in real time. The purchase cost for a quantity of one is $6,500 for Autosense I and $10,000 for Autosense II.

3.3.2.4 Composite System

It is possible to design a truck monitoring system that is a composite of more than one system. The motivation behind this option is optimizing the best features of both technologies being used.

3.4 GROUND TRUTH SYSTEM

The ground truth system selected for this project was a vehicle classifier with the capability of using either inductive loops or piezoelectric sensors, or both. Researchers would have selected classifiers similar to ones being purchased by TxDOT, although their current systems did not have the necessary features to accomplish this research. To serve as a ground truth system, the classifier must be able to do the following: monitor and store vehicle-specific data, be accurate and reliable, be flexible in its application, have the appropriate memory storage for several days of data collection, and be reasonably priced. The classifier selected was an International Road Dynamics Traffic Counter/Classifier (TCC) 540. The most accurate detector configuration for speed and classification data using this hardware would have been two piezoelectric sensors and one inductive loop. The initial tests in College Station used this configuration; however, in the interest of time, researchers decided not to install the piezo sensors at the Pharr district site. The resulting system classified vehicles based on length only and ignored number of axles and axle spacing. Speed accuracy would have also been compromised slightly but this was not deemed a problem. It should be noted that the classifier system was always a possible primary detection system if non-intrusive systems failed.

Vehicle classification systems have been used for several years and have proven their reliability over time. Their costs are not prohibitive and their accuracy is sufficient for this research. In recent research conducted at the Georgia Institute of Technology *(48)*, 13 sensor and classifier configurations from 10 commercially available equipment vendors were tested to determine their accuracy in classifying vehicles into 13 Federal Highway Administration (FHWA) classes. Classification accuracies ranged from 78.8 percent to 96.2 percent (combining class 2 and class 3 vehicles). The classification of class 9 vehicles (the majority of large trucks) was very good on most classifiers. Based on TTI tests, the speed accuracy of pavement classifiers can be as close as plus or minus one percent. A sophisticated classifier with extended memory costs approximately $2,000.

3.5 RECOMMENDATIONS

TTI recommended purchasing the following elements to accomplish the vehicle detection necessary in this project. Some of the elements are for the pavement sensor system that will be used for "ground truth" to judge the accuracy of the selected system. Table 3-2 summarized the pertinent features for the selection process. Based on these criteria, TTI recommended selection of the IRD acoustic sensor and the Schwartz Autosense II active infrared sensor for testing. Although IRD anticipated completing enhancements to its acoustic detector system by mid-August, 1996, its testing and availability were delayed. Beginning with its earliest tests by TTI and continuing to the present, the IR system by Schwartz performed well. Therefore, the Schwartz system appears to be the better choice for this project. Costs of the various elements that were purchased are shown in Table 3-5.

3.6 INITIAL FIELD TESTING

To evaluate the Schwartz Autosense II (AS2) infrared detection system and the International Road Dynamics (IRD) SmartSonic acoustic sensor, TTI used its test site on State Highway 6 in College Station. This test site offered the necessary verification equipment to test the non-intrusive sensors. Ground truth roadway sensors included inductive loop detectors (ILD) and two permanent piezoelectric sensors, combined and used as a system. The IRD TCC-540 classifier stored data from these sensors for comparison with non-intrusive sensor data. Other equipment included a portable trailer-mounted Burle color camera, with variable focal lengths ranging from six to 60 millimeters. An Integrated Services Digital Network (ISDN) line transmitted data and video to TTI's TransLink® lab using a remote Industrial PC computer

Table 3-5. Project Equipment Costs [a]

Item	Qty.	Unit Cost	Total Cost
Node computer	1	$3,310	$3,310
Vehicle classifier	1	2,555	2,555
Portable piezo sensors (1.8 m (6 ft))	8	321	2,568
Permanent piezo sensors (1.8 m (6 ft))	4	695	2,780
Polyguard	1	250	250
Temporary inductive loops	4	50	200
Cabling and other hardware	1	500	500
Active infrared detector	1	9,750	9,750
Acoustic detectors (2 lanes)	1	4,975	4,975
Pole and Mast arm	1	4,999	4,999
TOTAL			$31,887

[a] As of November 21, 1996
[b] Ship directly to Pharr District office.

equipped with the software PC Anywhere and a video compression system from PictureTel. Each sensor gathered data simultaneously, yet independently of other sensors. The first step in calibrating the TCC system was to verify its speed accuracy with a detuned radar gun. Once its speed accuracy was established, the TCC system served as the baseline speed and count system by which the non-intrusive systems could be judged. The video camera and a video cassette recorder also served as a verification system by recording site video for vehicle count and classification tests. Once the data from test and baseline systems were stored in a useable format, TTI personnel used SAS and Excel software to judge detector accuracy.

Figure 3-4 shows the test site layout. Site facilities include an overhead bridge at F.M. 60 (University Drive) and will eventually include a 12.2 m (40 ft) pole at the site for mounting sensors. Newly installed bridge mounting hardware and underground conduit facilitated testing of the Schwartz Electro Optical infrared sensor over the right southbound lane. During this initial test period, TTI learned that the acoustic detectors did not perform their best mounted on an overhead bridge structure (based on Minnesota GuideStar testing *(47)*), so limited testing utilized one of TTI's mobile data collection trailers placed beside the roadway with the sensor placed

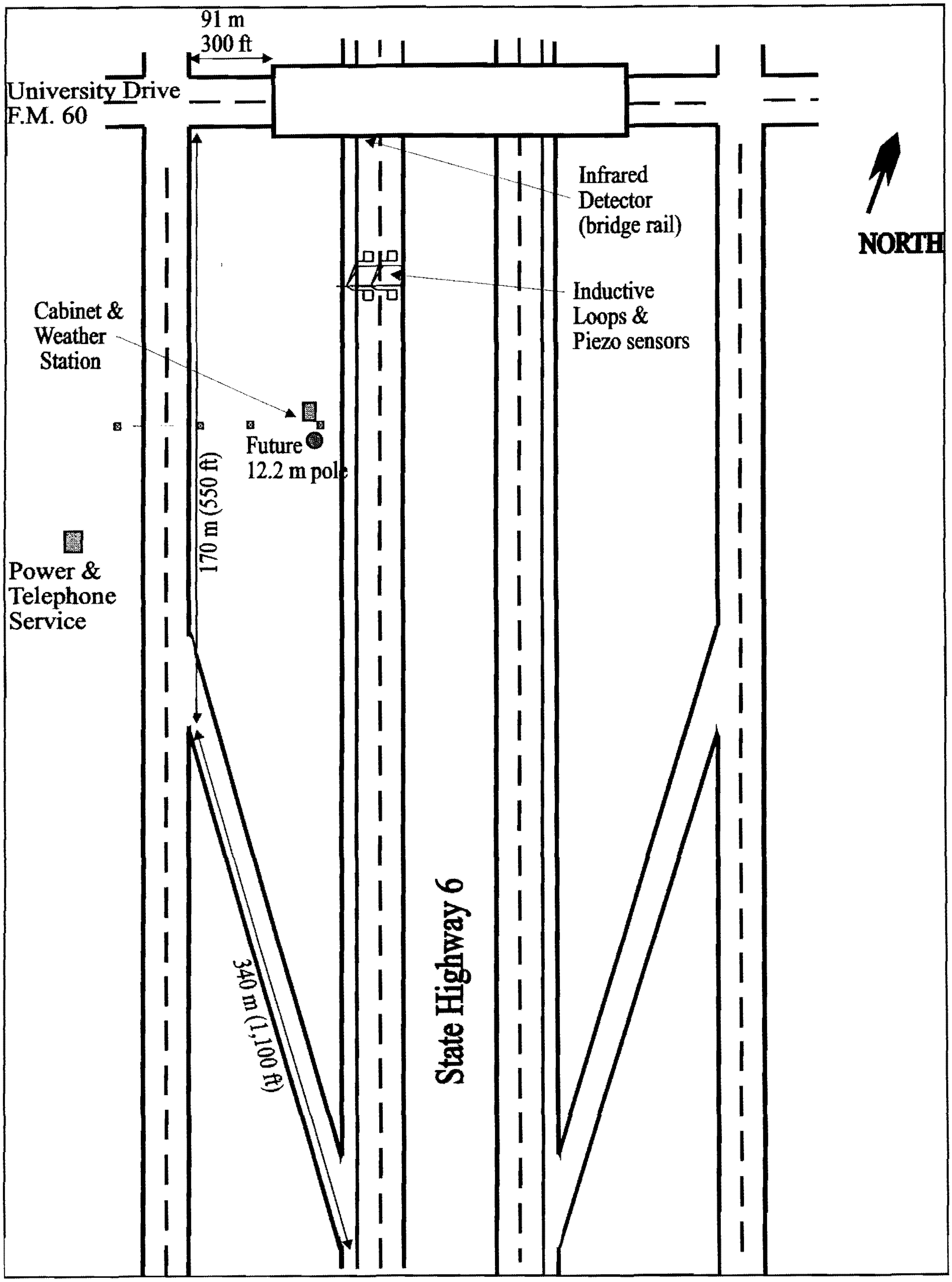


Figure 3-4. TTI Test Site in College Station

approximately 7.6 m (25 ft) high. The initial tests were intended to test the detection accuracy of the infrared and acoustic sensors, so this testing did not necessarily require a signalized intersection. However, the sensors would have to be accurate for high-speed detection, so this site worked well. The speed limit on S.H. 6 was 110 km/h (70 mph). The directional peak hour volume for the southbound direction at the test site was approximately 2,000 vph.

3.6.1 Test Site Set-up

TTI installed the Autosense II (AS2) system on the F.M. 60 (University Drive) bridge 6.7 m (22 ft) above the outside lane of southbound Texas S.H. 6 and centered over the lane. The mounting hardware had recently been fastened to the bridge structure, so only a mounting bracket for the sensor was required. Mounting of the sensor required traffic control, closing the outside lane because of risks associated with working over an active traffic lane. Communication and power leads connected the bridge location with a Type "P" roadside cabinet where the Industrial PC was located 150 m (500 ft) downstream from the bridge. The system required a DOS-based computer for operation and data collection. Communication via serial port allowed information to be transferred to and from the sensor at a high rate of speed.

Approximately 61 m (200 ft) downstream of the F.M. 60 bridge were the two piezoelectric sensors and ILDs that were used for classifiers or weigh-in-motion equipment. The inductive loop configuration facilitated their use either with or without the axle (piezo) sensors for vehicle classification and speed data collection. When used without axle sensors, classification is based on length, whereas with axle sensors, classification is based on axle spacing. This project used both ILDs and axle sensors during testing in College Station, but subsequent testing in the Pharr district used only ILDs.

The classification instrument TTI used in this project was an International Road Dynamics TCC/540. In-road permanent piezoelectric sensors gave very accurate speed and classification information on each vehicle, unless the vehicle missed one of the two sensors. Staff verified its speed accuracy using a radar gun. Data reduction utilized the classifier's time stamp for each vehicle to compare with vehicle speeds and classifications from test systems. Of course, this required coordinating each system's internal clock to a common clock time to subsequently match individual vehicles.

3.6.2 Video Data

TTI also recorded video of the detection area in order to further verify the accuracy of sensors. Again, the video recorder's internal clock also required coordination with the common clock time of other test systems. Video data allowed systems to be matched visually according to each vehicle's time as it traversed the detection area. This study team defined both single-unit vehicles and combination vehicles as "trucks" for purposes of this study. Project staff allowed each detector to operate for a sufficient length of time to generate data for comparison. The downloaded data then provided the basis of comparison with the ground truth system. The video system provided another means of verification for all systems.

3.6.3 Radar

TTI used a detuned KR-11 radar gun to measure speed as vehicles passed in free-flow conditions along the highway. As each vehicle of interest passed under the Autosense II system, an observer recorded its speed and clock time for subsequent comparisons. The AS2 detector wrote its detection data and time stamp to the Industrial PC for later retrieval and comparison. This same procedure was also used for the SmartSonic analysis.

3.6.4 Detector Data Analysis

Table 3-6 shows statistics for the radar speeds and infrared speeds. Radar speeds indicated a mean truck speed of 98.1 km/h (61 mph) for a sample of 66 vehicles. The infrared sensor measured a mean truck speed of 107.8 km/h (67 mph) for the same 66 vehicles. The radar speed had a standard error of 0.49 and a range of 27.4 km/h (17 mph), while the infrared sensor measured a standard error of 1.04 and a range of 93.3 km/h (58 mph). The standard deviation of the radar was 3.97 compared to a standard deviation of 8.44 for the infrared. The infrared speed showed a 6.4 km/h (4 mph) higher standard deviation and a range 66 km/h (41 mph) higher than the radar speed. The extreme range of the infrared speed resulted from the maximum of 165.7 km/h (103 mph) generated by one observation.

Table 3-6. Radar Speed vs. Infrared Speed

	Radar Speed km/h (mph)	Infrared Speed km/h (mph)	Matched R and IR km/h (mph)
T-Stat			-13 (-8)
Mean	98 (61)	108 (67)	-10 (-6)
Standard Deviation	6 (4)	13 (8)	-10 (-6)
Sample Variance	26 (16)	114 (71)	69 (43)
Range	27 (17)	93 (58)	76 (47)
Minimum	84 (52)	72 (45)	-64 (-40)
Maximum	111 (69)	166 (103)	11 (7)
Sum	6,457 (4,013)	7,117 (4,423)	-660 (-410)
Count	66	66	66
Largest (1)	111 (69)	166 (103)	11 (7)
Smallest (1)	84 (52)	72 (45)	-64 (-40)

A plot showing the TCC/540 speeds versus the infrared speeds is shown in Figure 3-5. This plot shows the speed measured by each system for every vehicle recorded and allows a comparison to be made. Figure 3-6 shows the speed differences between the TCC/540 and infrared systems for every vehicle analyzed. As can be seen, most speed differences between the two systems measured less than 10 km/h (6.2 mph).

While these statistics gave some indication of the accuracy of the infrared system, it revealed little about its accuracy on an individual truck basis. Researchers found that radar speeds were reasonably accurate, so the infrared detector should desirably generate similar results. Staff ran a paired *t*-test on the sample to determine if the data were significantly different. Table 3-7 provides results of this comparison. The *t*-value generated for the different paired observation speeds was -7, rejecting the null hypothesis of no difference between the two systems. This indicated that the infrared system did not give significantly accurate individual vehicle speeds.

Table 3-7. Paired t-Test Results: Radar and Infrared

	Radar Speed km/h (mph)	Infrared Speed km/h (mph)
Mean	98 (61)	108 (67)
Variance	26 (16)	114 (71)
Observations	66	66
Pearson Correlation	0.7	
Hypothesized Mean	0	
Difference	65	
t-Statistic	-8	
P(T<=t) one-tail	6E-11	
t Critical one-tail	2	
P(T<=t) two-tail	1E-10	
t Critical two-tail	2	

Staff followed similar steps in comparing another infrared detector data set matched with vehicles in a data set from the piezo classification system (TCC). Tables 3-8 and 3-9 indicate the results. The sample mean as measured by the piezo system was 96.5 km/h (60 mph) compared to the infrared mean of 103 km/h (64 mph). The standard error for the piezo was 0.41 for a range of 43.4 km/h (27 mph) and a standard deviation of 8.2 km/h (5.1 mph). The infrared's standard error was 0.8 for a range of 146.4 km/h (91 mph) and its standard deviation was 16.1 km/h (10 mph). These numbers indicate more scatter or spread in the infrared data than in the TCC data. The *t*-test also failed the null hypothesis of no difference. This indicates that there was also a significant difference in speed measurement for individual vehicles between these two systems. Results of these analyses also show that the mean values of infrared detector speeds were higher than either the radar or the TCC system.

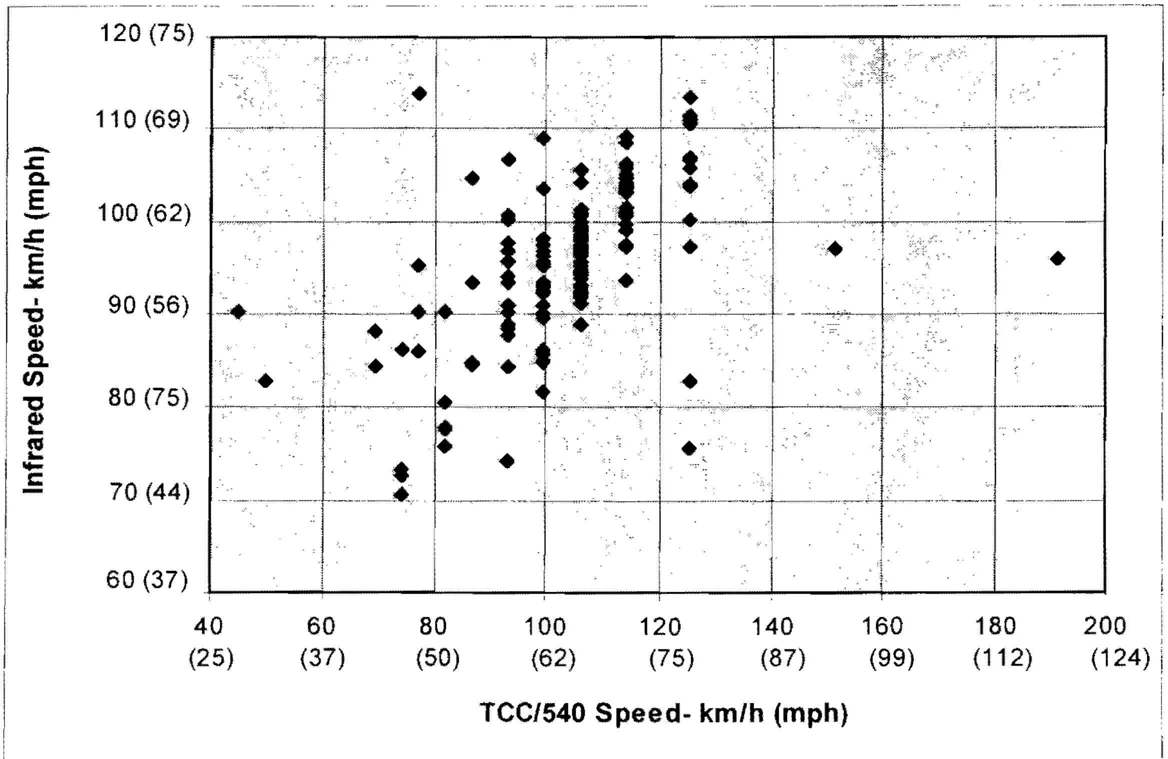


Figure 3-5. TCC/540 vs. Infrared Speeds

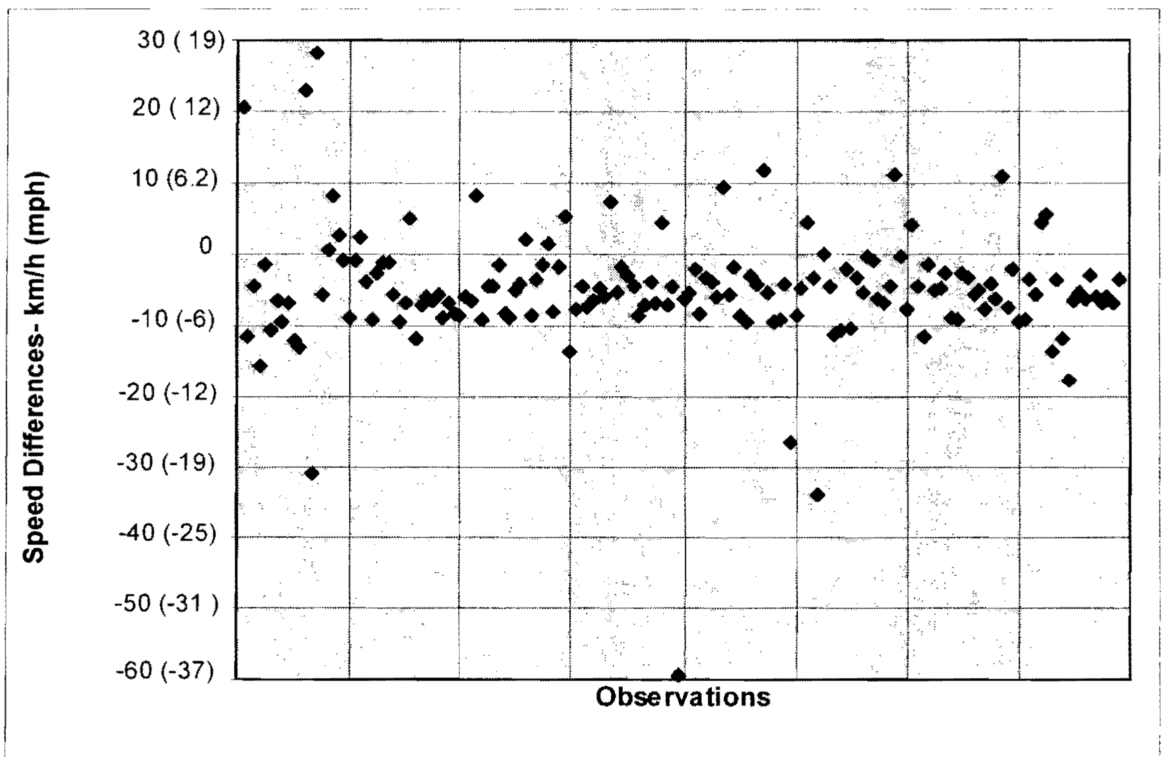


Figure 3-6. Speed Differences Between TCC/540 and Infrared

Table 3-8. Infrared Speed vs. TCC Speed

	Infrared Speed km/h (mph)	TCC Speed km/h (mph)	Matched IR & TCC km/h (mph)
t-Statistic			-11 (-7)
Mean	103 (64)	97 (60)	-8 (-5)
Standard Deviation	16 (10)	8 (5)	14 (9)
Sample Variance	161 (100)	43 (27)	117 (73)
Range	146 (91)	43 (27)	142 (88)
Minimum	45 (28)	71 (44)	-95 (-59)
Maximum	191 (119)	114 (71)	45 (28)
Sum	16,383 (10,182)	15,146 (9,413)	1,237 (-769)
Count	158	158	158
Largest (1)	191 (119)	114 (71)	45 (28)
Smallest (1)	45 (28)	71 (44)	-95 (-59)

Table 3-9. Paired t-Test Results: TCC and Infrared

	Infrared Speed km/h (mph)	TCC Speed km/h (mph)
Mean	97 (60)	103 (64)
Variance	43 (27)	161 (100)
Observations	158	158
Pearson Correlation	0.5	
Hypothesized Mean Difference	0	
Difference	157	
t-Statistic	-7	
P(T<=t) one-tail	1E-11	
t Critical one-tail	2	
P(T<=t) two-tail	3E-11	
t Critical two-tail	2	

Figure 3-7 is a scatter plot of radar speeds against infrared speeds of matched vehicles. Figure 3-8 plots speed differences between radar and infrared speeds for each vehicle observed. Like the differences between the TCC/540 and infrared speeds, most of the speed differences between the radar and infrared speeds fell within 10 km/h (6.2 mph).

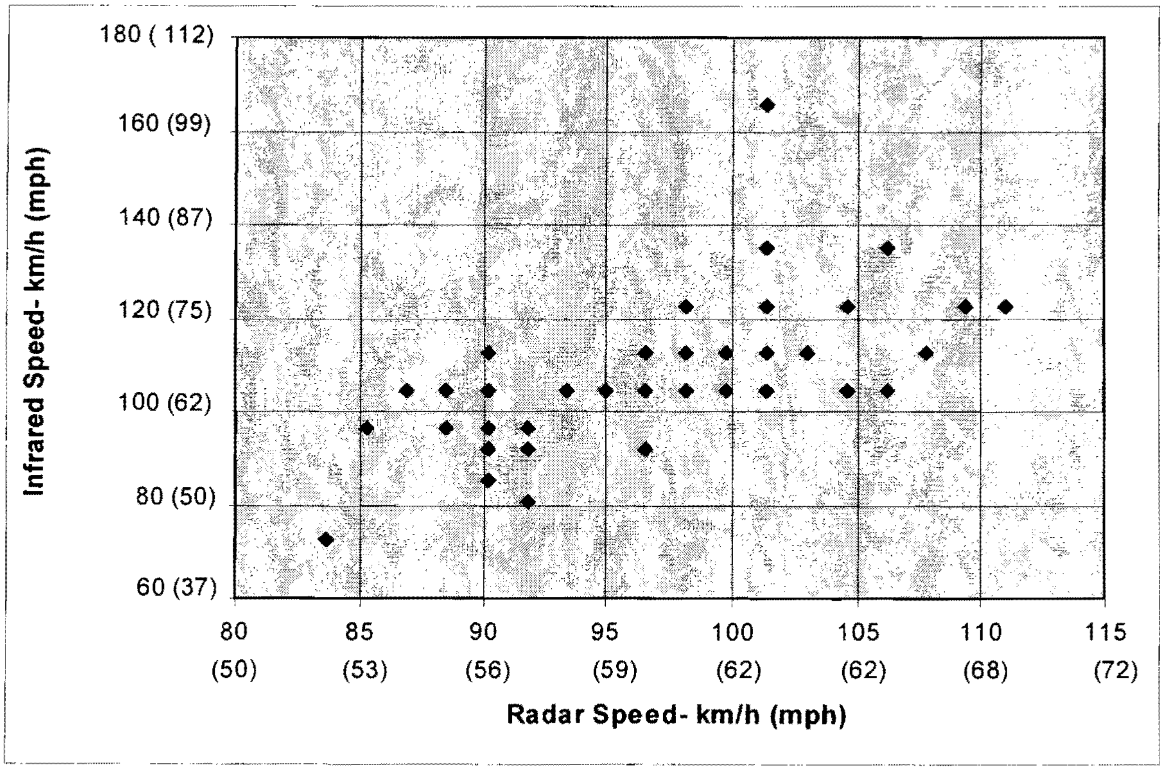


Figure 3-7. Radar vs. Infrared Speeds

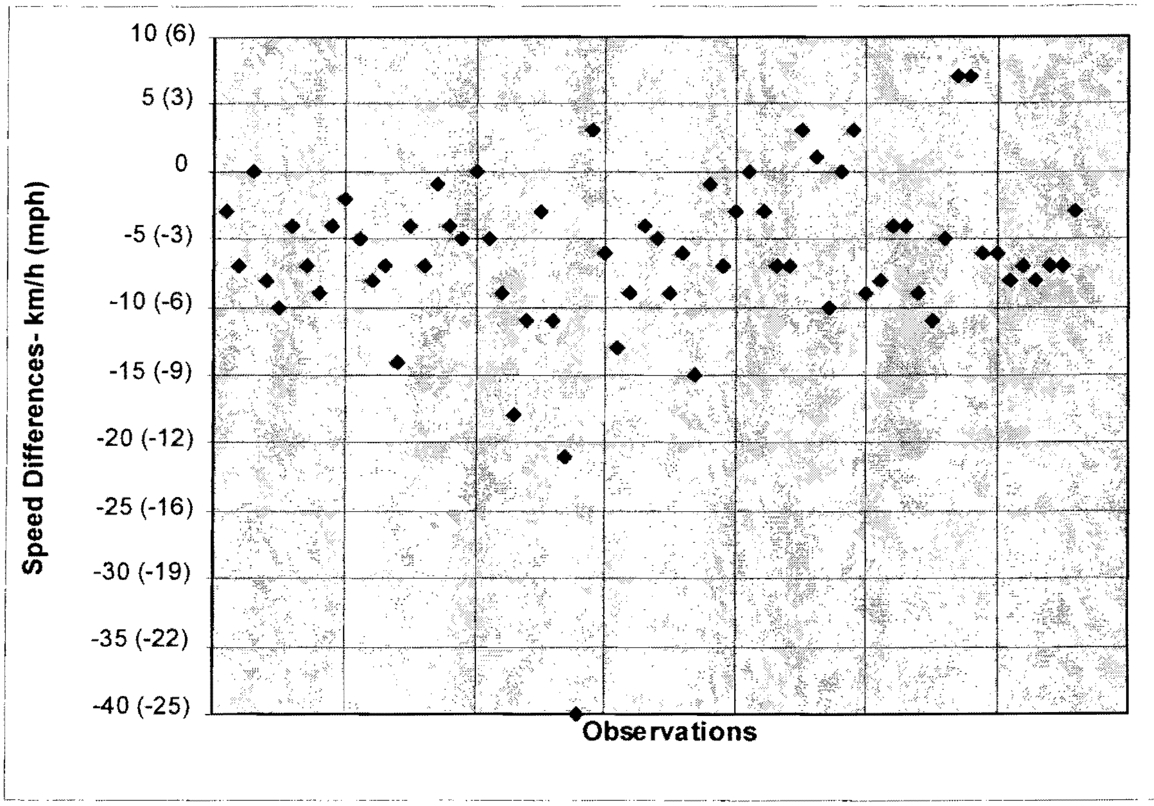


Figure 3-8. Speed Differences Between Radar and Infrared

Review of the videotape revealed that the infrared system, the TCC system, and hand-held radar units all missed vehicles. Vehicles missed by radar resulted due to operator error or the radar gun not being ready due to vehicles passing at short headways. As shown in Table 3-10, the infrared system missed only 3.12 percent of the 160 vehicles included in this sample, whereas the TCC system missed 8.75 percent of the total vehicles. The infrared system missed five trucks -- four tractor semi-trailers and one single unit truck. It may have missed two of the tractor semi-trailers due to their short length. On the other hand, the TCC system missed more single unit vehicles than combination vehicles. It missed a total of 14 vehicles -- 10 single units and four combination vehicles.

Table 3-10. Frequency of Missed and Misclassified Vehicles[a]

	No. Missed	Percent Missed	No. Misclassified	Percent Misclassified
Infrared	5	3.12	12	7.5
TCC	14	8.75	12	7.5

[a] Total Number of Vehicles Observed = 160

Both the infrared and the TCC systems misclassified 7.5 percent of the 160 vehicles detected, as shown in Table 3-10. In three instances, the infrared and TCC both misclassified the same vehicles. These vehicles included an ambulance, a pick-up closely followed by a van, and an instance where a tractor-trailer changed lanes as it passed the sensors. Pick-up trucks pulling trailers or campers represented the most frequently misclassified vehicle. The infrared detected this combination six times and the TCC seven times. Other vehicles misclassified by the infrared included a tall van, a motor home, and an instance where several cars followed each other in close succession. The TCC misclassified a large flatbed truck. Also, an instance occurred where a tractor-trailer changed lanes after passing the infrared in the unmonitored lane and was detected by the TCC after switching to the monitored lane.

4.0 SOFTWARE DEVELOPMENT

4.1 INTRODUCTION

The purpose of this project is to use new technologies to monitor, in real-time, large vehicles approaching a high-speed signalized intersection and minimize their stops and delays. The system developed as part of this research will accomplish project objectives by extending the green time to allow commercial vehicles to pass through without conflict if the signal is already green. The research used two new sensor technologies to detect trucks, an infrared sensor Autosense II (AS2) by Schwartz Electro-Optics Inc. and an acoustic (sonic) sensor SmartSonic TSS-1 by International Road Dynamics (IRD). The system selected to provide verification data for the two non-intrusive systems above was a system of inductive loop detectors (ILD) connected to a TCC-540 International Road Dynamics vehicle classifier.

The TTI research team developed software programs to communicate with the sensors via an RS-232 serial port, receive data messages sent by the sensors for vehicles they detect, analyze the data messages to identify large vehicles approaching the intersection with high speeds, and make a decision in real-time regarding extending the green. The decision criteria are vehicle speed and classification. The programs developed by TTI reside on an Industrial PC placed in a cabinet at the test intersection being monitored in Sullivan City, Texas. The following paragraphs discuss the hardware and software components of the system developed by TTI, the data messages generated by each system for detected vehicles, the different options for extending the green time and the option adopted for this system, and finally the system configuration parameters.

4.2 SOFTWARE AND HARDWARE COMPONENTS

All three sensor technologies evaluated in this study have the ability to communicate the data they generate for detected vehicles over an RS-232 serial port. However, each of these three sensors has its own unique serial communications protocol to communicate with other systems and each sensor generates a different set of data items for the vehicles it detects. The software programs developed by TTI consist of three main modules: the serial interface module, the large vehicle identification module, and the green extension module. Due to differences noted above between the systems, project staff developed a unique version of the serial interface module and the large vehicle identification module for each sensor system. Staff chose a step-wise or incremental approach in the software development and testing of the three sensor systems for several reasons. One was simply because there were delays in deliveries of the acoustic detector. Another reason was readiness of sensors for serial communications upon arrival from the manufacturer. Finally, there would be difficulty in isolating problems with a given sensor if the software was written to run all the sensors together. TTI has not fully tested the SmartSonic system due to problems encountered in getting the system to work properly and delays in receiving the serial communications protocol specifications from the manufacturer. The following is a description of the three software modules.

4.2.1 Serial Interface Module

The serial interface module establishes a serial connection to a sensor over one of the serial ports on the industrial PC. The industrial PC has 6 serial ports. The serial connection enables the TTI software to receive, in real-time, data from the sensors every time a vehicle is detected and to send command messages to the sensors to configure or reset them. The connection is established by using serial communications protocol specifications provided by the sensor manufacturer including: baud rate, number of data bits, parity, number of stop bits, flow control, and command message formats. Once the connection is established to a sensor, data are received continuously from that sensor every time a vehicle is detected. The received data are stored in a memory buffer to be analyzed by the large vehicle identification module. In addition to storing the data in a memory buffer, the received message/messages from the sensors are logged into daily log files. The daily log file names conform to the following naming convention: "month_day_year.xxx." The data file extensions are either ".TCC" for the TCC-540 classifier, ".AS2" for the AS2 sensor, or ".SON" for the Sonic sensor.

The TCC system sends one data message for every vehicle it detects. The data message consists of four fields: a time stamp, lane number where the vehicle was detected, vehicle length, and vehicle speed. However, the AS2 system generates five data messages for every vehicle it detects. The fifth message generated by the AS2 contains the complete data about the detected vehicle and is usually sent by the system after the vehicle completely clears the sensor area. The fifth message consists of several fields including: vehicle height, vehicle length, vehicle class, and vehicle speed.

4.2.2 Large Vehicle Identification Module

The large vehicle identification module analyzes the data messages received from a sensor by the serial interface module and stored in a memory buffer. It determines if the detected vehicle is a large vehicle and is traveling at a speed that requires a green extension to allow it to pass through the intersection without conflict. The data parameters provided by the sensors and used to classify vehicles differ from one system to the other. For example, the length data parameter from the TCC classifier is used to identify large vehicles. On the other hand, the height data parameter from the AS2 sensor is used to identify large vehicles. The height data parameter is more accurate than the length data parameter provided by the AS2 sensor. Vehicles detected by the TCC and have a length of greater than 6.09 m (20 ft) are considered large vehicles. The AS2 considers vehicles detected with a height of 2.28 m (7.5 ft) or greater to be large vehicles.

Once a vehicle is classified as large, the software checks the vehicle speed to determine if it requires extension of the green time for the designated approach. If the vehicle's speed is greater than 72 km/h (45 mph), the software invokes the Green extension module to extend the green time for the designated approach by 3 seconds. If the vehicle's speed is less than 72 km/h (45 mph) but greater than 24 km/h (15 mph), the green time is extended by 4.5 seconds. The green time is not extended for large vehicles with speeds less than 24 km/h (15 mph). The green time extension interval depends upon the vehicle's speed, the distance from the sensor to the stop line, and the time needed by the vehicle to pass through the intersection without conflict.

4.2.3 Green Extension Module

TTI considered two methods for extending the green time for a designated approach: Phase Extension and Phase Hold. Both methods are contact-closure methods and require sending a signal over a wire connected to the designated approach's phase-extension or phase-hold on the controller's back panel. The Phase Extension method extends the minimum green time for the designated approach by a constant number of seconds (called Phase Passage Time) every time a signal is sent to the Phase Extension connection. The green time for the designated approach would be extended until it reaches the Maximum Green time allowed for that approach. Once the Maximum Green time is reached, the phase will turn to yellow and then red as usual.

Although the Phase Passage Time is a configurable phase parameter in the controller, it must be manually changed using the controller's front panel or downloaded from a laptop computer. However, in the Phase Hold method, the green time can be extended dynamically for the duration of the signal that is sent to the Phase Hold connection. It is not constant and the user can specify the length of the signal through TTI's program. For both methods, trying to extend the green during the red phase does not affect the phase. On the other hand, trying to extend the green when the phase is already in green and there is ample green time left for a vehicle to pass through the intersection could have two different outcomes. It would increase the total green time in the Phase Extension method, but it would have no effect in the Phase Hold method. Staff chose the Phase Hold method because it gives more flexibility in extending the green time. The green time is extended by 3 seconds for large vehicles traveling at speeds of 72 km/h (45 mph) or higher and by 4.5 seconds for large vehicles traveling at speeds between 24 km/h and 72 km/h (15 mph and 45 mph). The green time is not extended for vehicles traveling at speeds lower than 24 km/h (15 mph). If a series of large vehicles is detected, the green time will be extended successively and the phase will be held for a maximum of 30 seconds. After 30 seconds, the signal sent to the Phase Hold connection would be disconnected and the phase is allowed to turn to red.

The signal is sent from the PC to the phase hold connection through hardware components acquired from National Instruments Inc. The hardware components bought from National Instruments include: a PC Digital I/O card capable of receiving or sending 24 digital I/O signals, Digital Output Modules that can convert DC voltages from as low as 3.3 volts up to 32 volts direct current (VDC), and other cables and accessories to house the I/O modules and connect the different components together.

4.2.4 Hardware Components

The hardware components for accomplishing project objectives are as follows:

- A Pentium 133 MHZ industrial PC with 16MB of RAM, 3 PCI slots, 4 ISA slots, and 2 serial ports;
- A serial communications card with four additional RS-232 serial ports;
- A PC-DIO-24 digital I/O card, an SSR Series 8-Channel Backplane, and 3 Digital Output Modules from National Instruments Inc.;
- A Remote Power On/Off module that allows remote startup and shutdown of the system over a telephone line; and
- A 28.8 US Robotics external modem.

4.3 SYSTEM CONFIGURATION PARAMETERS

TTI research staff designed the software programs to be configurable and very flexible. System parameters that can affect the performance of the system are placed in a text file named "Truck.ini" that can be edited using any text editor. Modifications to system parameters take effect the next time a user runs the program following modification. Programs are located in a subdirectory named "C:\Sullivan\Apps" on the industrial PC. There are three program applications in that subdirectory called AS2.EXE, TCC.EXE, and AS2TCC.EXE. The first two programs communicate with one sensor at a time. The AS2.EXE communicates with the AS2 sensor, and the TCC.EXE communicates with the TCC classifier. The third application AS2TCC.EXE monitors both sensors at the same time. Figure 4-1 shows a flowchart for the AS2TCC.EXE application. Each one of these applications displays a message in a window on the PC screen every time a large vehicle that requires extension of the green time is detected by the sensor.

The message displayed for large vehicles detected by the AS2 includes: a time stamp, vehicle height, vehicle length, vehicle speed, and number of seconds the green time is extended. The message displayed for vehicles detected by the TCC includes: a time stamp, lane number where the vehicle was detected, vehicle length, vehicle speed, and number of seconds the green time was extended. The AS2 sensor is installed to monitor the outer lane only while the TCC monitors both lanes of the intersection in Sullivan City. The combined program (AS2TCC.EXE) polls the AS2 sensor first at a frequency of every 200 milliseconds to determine if it has detected any vehicles. If the vehicle detected is large and requires a green extension, the system sends a signal to the controller cabinet to extend the green time for the duration of that signal. The system saves into the daily log file for the AS2 sensor all vehicle detections received from that sensor.

The system checks the TCC classifier next. The system saves detection data in the daily log file for the TCC immediately and does not check for large vehicles if the AS2 system has found a vehicle that required extension of the green time. If the AS2 did not detect a large vehicle that required extension of the green time, it analyzes data received from the TCC. If a large vehicle requiring extension of the green time is detected, it extends the green time. This scenario might occur because the TCC is monitoring both lanes while the AS2 is monitoring only one lane. It might also happen if the vehicle height is less than 2.3 m (7.5 ft) and the AS2 sensor would reject the vehicle as a large vehicle. On the other hand, the length of the same vehicle detected by the TCC might be greater than 6.1 m (20 ft) and it would be classified as a large vehicle. The system generates warning messages of potential sensor problems on the monitor if no data are received from the AS2 sensor or the TCC classifier within a time period of five minutes. The system parameters file is also located in the same directory as the programs. The following is a description of the system configuration parameters included in the "Truck.ini" file:

- AS2_ComPort: specifies the serial port on the industrial PC where the AS2 sensor is connected,
- AS2_BaudRate: specifies the number of bits per second, i.e., data transfer rate required to communicate with the AS2 sensor,
- AS2_Parity: specifies the form of error detection used by the system to check the integrity of the data transmitted,
- AS2_NoDataBits: specifies the number of bits per character transmitted,
- AS2_StopBit: specifies the character end,
- AS2_Cutoff Height: specifies the height in feet above which vehicles detected by the AS2 would be classified as large vehicles,
- AS2_MaxNoResponseTime: the maximum number of minutes that has to pass without receiving any data from the AS2 sensor before trying to reinitialize the sensor. A message will be displayed to warn the user of potential problems with the sensor,
- TCC_ComPort: specifies the serial port on the industrial PC where the TCC is connected,
- TCC_BaudRate: specifies the number of bits per second, i.e., data transfer rate required to communicate with the TCC sensor,

- TCC_Parity: specifies the form of error detection used by the system to check the integrity of the data transmitted,

- TCC_NoDataBits: specifies the number of bits per character transmitted,

- TCC_StopBit: specifies the character end,

- TCC_Cutoff Length: specifies the length in feet above which the program would classify vehicles detected by the TCC as large vehicles,

- TCC_Passwd: the password needed to connect to the TCC classifier,

- TCC_MaxNoResponseTime: the maximum number of minutes passing without receiving any data from the TCC classifier before attempting to reinitialize the device and warning the user of potential problems with the classifier,

- CutoffSpeed: the speed below which the green time would not be extended for large vehicles,

- MaxCallTime: the maximum number of seconds that the green time would be extended for large vehicles detected in succession before allowing the phase to turn to red,

- SpeedForExtension: the speed above which green time would be extended by 3 seconds for large vehicles,

- Extension1: the number of milliseconds green time would be extended for large vehicles traveling at speeds of 72 km/h (45 mph) or above, and

- Extension2: the number of milliseconds green time would be extended for large vehicles traveling at speeds lower than 72 km/h (45 mph) but higher than 24 km/h (15 mph).

Figure 4-1 is a flow chart showing the primary steps involved in the processing as a truck approaches the intersection. It assumes the use of the TCC and the Autosense II detectors because preliminary data from the IRD acoustic system indicated that it was not as accurate as the other two systems. It also assumes that a truck could be detected by either system and, based on its speed, the TTI system would send a signal to the Phase Hold to extend the green by either 3.0 seconds or 4.5 seconds. A detected truck traveling 24 km/h (15 mph) or slower would be ignored.

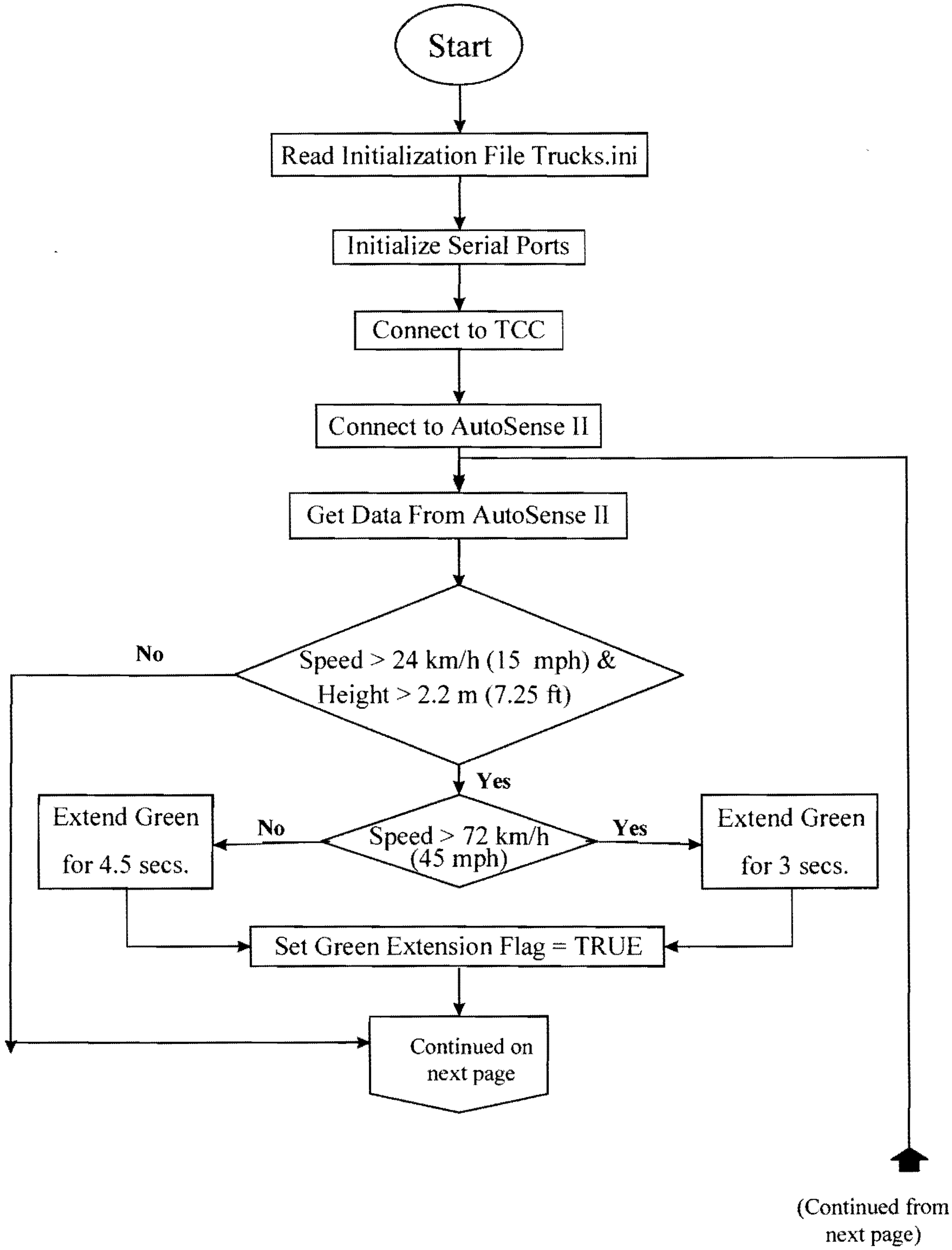


Figure 4-1. Flowchart of As2Tcc.exe Program

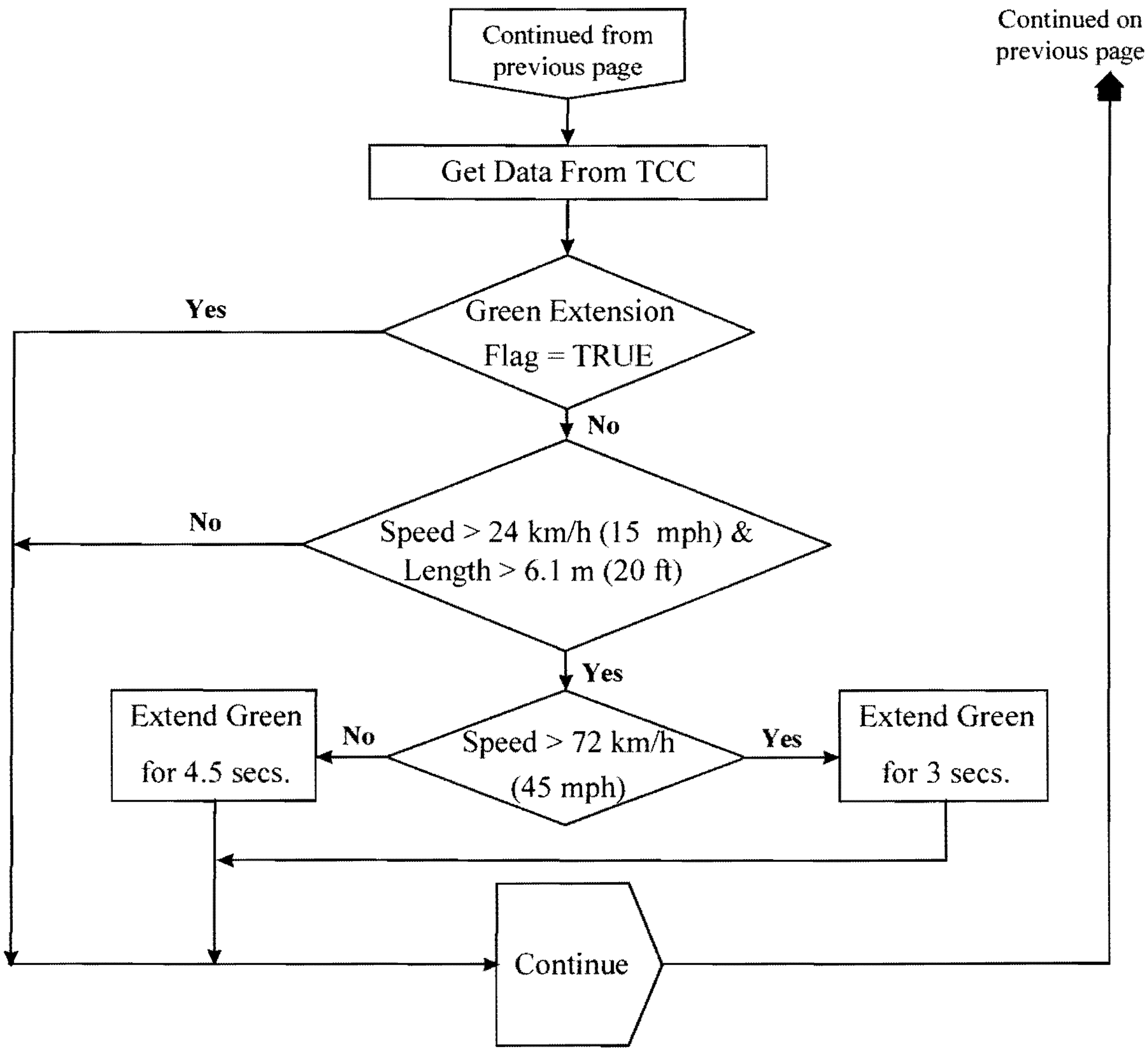


Figure 4-1. Flowchart of As2Tcc.exe Program (Continued)

4.4 INITIAL TESTING OF GREEN EXTENSION VIA PHASE HOLD

The software developed by the TTI research team for this project consists of three modules: the serial interface module, the large vehicle identification module, and the green extension module. TTI tested the first two modules at TTI's State Highway 6 test site in College Station, Texas. However, early plans to use a local on-line controller did not materialize. Also, TTI did not have access to a properly equipped controller cabinet at its test site to test the green extension module. Therefore, the research team used its full-scale cabinet located in the TransLink™ laboratory in the TTI Building on the campus of Texas A&M University to test the green extension module.

The purpose of the green extension module was to extend the green time by a set number of seconds to enable large vehicles to pass through the intersection without conflict if the signal was already green. If the signal was red, this module had no effect whatsoever on signal timing. The mechanism used to extend the green was a contact-closure mechanism. It consisted of sending a signal to the phase-hold connection of the designated phase on the controller's back panel for the duration of the green time extension. In order to accomplish this task, researchers acquired from National Instrument's Inc. a digital I/O card, three digital output modules, and other accessories to house the modules and connect the PC card to the phase-hold connection through the digital output modules. The setup in the TransLink™ laboratory consisted of a complete controller cabinet, an Eagle EPAC 300 controller, the industrial PC, and the National Instrument equipment connected to the phase-hold connection of one the controller's phases.

TTI simulated large vehicle arrival through its software and observed the green extension module extending the green by sending a signal to the phase-hold connection of the designated phase. The system extended green time by 4.5 seconds for large vehicles traveling at a speed greater than 24 km/h (15 mph) and less than 72 km/h (45 mph). It extended the green time by 3.0 seconds for large vehicles traveling at speeds faster than 72 km/h (45 mph). The TTI system extended the green time via a signal to the phase hold only when the phase was already in green. The controller ignored the phase-hold signal if the phase was in red.

5.0 TRUCK STOPPING DISTANCE CONSIDERATIONS

5.1 INTRODUCTION

Truck stopping distances are greater than those of smaller vehicles. Truck drivers on high- speed approaches to signalized intersections attempt to maintain their speed through the intersection to keep from being delayed. Extending the green indication for some of the trucks will reduce these problems but this obviously cannot be done for all trucks. There is reason to evaluate the potential for identifying trucks as they approach intersections and modify the signal timing under the proper conditions to either facilitate their safe passage or ensure adequate stopping distance. Basic design practice has, for many years, used the passenger car as the design vehicle assuming that the driver eye height advantage for truck drivers compensates for the additional stopping distance. Unfortunately, this is not always true. This chapter evaluates the stopping requirements for large trucks to determine implications at signalized intersections.

The braking performance of heavy trucks and combination vehicles is inferior to that of passenger cars. The optimal design of braking systems for large trucks is much more complex than simply installing bigger brakes to match the heavier loads. One of the problems is that, at least before anti-lock braking systems (ABS) on large trucks, brakes that were properly designed for a loaded truck were not necessarily designed properly for an unloaded truck, especially in a panic stop application.

When the driver of a large truck applies the brakes, the air braking system does not respond immediately. An air brake system inherently delays full application of brakes. This is unlike passenger car brakes using hydraulic braking which respond instantaneously. The delay in trucks, of course, increases their stopping distance as compared to automobiles. Federal rules require full brake application on tractors in 0.45 seconds and on trailers in 0.30 seconds. Unfortunately, connecting a tractor and trailer whose individual brake systems are not perfectly compatible increases the braking distance even more. Delay between pedal actuation and full brake application increases to a full second or more *(49)*.

5.2 FEDERAL BRAKING REQUIREMENTS

Review of the literature pertaining to truck stopping distance indicates that truck stopping distances were regulated as specified in the Uniform Vehicle Code (UVC) of 1955, 1963, and 1974. Another regulatory requirement came through the U.S. Department of Transportation (DOT), Federal Highway Administration (FHWA) Motor Carrier Safety Regulations of 1974 *(50)*. This specified deceleration rates of 6.4 m/sec^2 (21 ft/sec^2) for passenger cars and 4.3 m/sec^2 (14 ft/sec^2) for truck combinations. In other words, a car should stop in two-thirds the distance required by a truck. These DOT regulations specified stopping distances for various trucks from a speed of 32 km/h (20 mph). For lightweight 2-axle trucks, the distance was 7.6 m (25 ft). For heavy two-axle trucks and three-axle trucks, it was 10.7 m (35 feet), and for combination trucks, this distance was 12.2 m (40 ft) *(51)*.

In July 1986, the U.S. Department of Transportation began rulemaking procedures to effect a change in the legal requirement for front (steer axle) brakes on trucks and truck tractors with three or more axles. This would eliminate an inconsistency or loophole in the law which had existed since 1952. In that year, the Federal Motor Carrier Safety Regulations (FMCSR) adopted the policy of allowing truck operators to remove brakes on steering axles for other than two-axle trucks. This change would result in the FMCSR being consistent with the requirement of the National Highway Safety Administration (NHTSA) specified in Federal Motor Vehicle Safety Standard (FMVSS) No. 121, *Air Brake Systems*. The new rule states that newly manufactured air braked vehicles must be equipped with brakes acting on all wheels. The Commercial Motor Vehicle Safety Act, which became law in October 1986, required FHWA to remove the front brake exemption within 90 days *(52)*.

Electronically controlled anti-lock braking systems typically provide benefits in an emergency situation by monitoring wheel rotation and modulating the brake pressure in order to prevent tire lock-up, or skidding. This may become critical at high-speed signalized intersections upon the onset of yellow and when road conditions are less than optimal. These ABS systems are sophisticated and complex, and their usage is already widespread on heavy vehicles. On September 28, 1993, the National Highway Traffic Safety Administration (NHTSA) published a Notice of Proposed Rulemaking, proposing to require ABS. The final rule on ABS was published by NHTSA on March 10, 1995. It requires ABS on all newly manufactured commercial vehicles as follows: 1) on/after March 1, 1997, truck tractors; 2) on/after March 1, 1998, all other air braked vehicles; and 3) on/after March 1, 1999, all hydraulically braked vehicles. Also, on March 10, 1995, the Federal Highway Administration (FHWA) Office of Motor Carriers published a notice of intent concerning maintenance policies for anti-lock brakes. The Class 8 vehicle Original Equipment Manufacturers (OEM) currently offer anti-lock brakes as standard equipment *(53)*.

5.3 FACTORS THAT AFFECT TRUCK BRAKING

A number of factors affect heavy vehicle braking performance. These include: tire type and condition, weight of the vehicle, pavement surface condition, the number of axles with brakes, and the condition of the brakes. Driver perception-reaction time is also an important factor in overall stopping distance considerations. The AASHTO Green Book *(54)* does not provide a unique driver reaction time for drivers of larger vehicles. However, in relation to truck stopping sight distance, it states that the distances proposed for design for passenger cars ". . . might be questioned for use in design for truck operation . . . ."

The tire-pavement surface interaction plays a part in stopping distance requirements. There was no evidence found in the literature to support the direct use of lower skid numbers for harder truck tires. Certainly, there is a difference in the composition of tires between the two vehicle types. The harder rubber used to achieve load-carrying strength and longer wear reduces the force developed at the tire-pavement interface. Tests conducted on wet asphalt using the American Society for Testing and Materials (ASTM) skid trailer yielded a value of 0.60 for a car tire, but only a value of 0.50 using a truck tire. Likewise, on a wet portland cement concrete pavement surface with an ASTM value of 0.35, a truck tire would yield a value of only 0.23. Truck tire traction is typically 65 to 85 percent of automobile tire values *(55)*.

Brake maintenance is also very important in achieving the minimum stopping distance, especially for trucks. Poorly maintained or disconnected brakes are detrimental to stopping characteristics of trucks. An important consideration is weight shift from braked axles to those that are unbraked. A good example is disconnected steer axle brakes. Loss of control is much more likely without front brakes besides the greatly increased stopping distance. A bobtail tractor without front brakes might only have an effective friction value of 0.34 compared to 0.40 assuming even weight distribution. This reduces braking efficiency by about 15 percent *(55)*.

In Bureau of Motor Carrier Safety (BMCS) field surveys in 1982, over 33,000 vehicles were inspected. Of this total, over 32,000 had violations of the Federal Bureau of Motor Carrier Safety Regulations. Brakes accounted for 37 percent of all violations, with 18 percent of the brake violations being serious enough to place the vehicle out-of-service. Another study *(56)* estimated that more than half of all air braked vehicles have one or more brakes out of adjustment. It further estimates that one-fourth routinely experience a reduction of 40 percent of braking potential because of poorly maintained brakes. Uneven braking can cause loss of control (jackknifing) on wet pavements. Because properly adjusted brakes perform more work, the heat build-up is greater.

5.4 RESULTS OF BRAKING TESTS

5.4.1 Optimum Conditions

Several studies have addressed stopping distance requirements of heavy trucks *(57,58,59,60)*. One must be careful, however, in simply comparing the results of these tests because each test represents a unique set of circumstances. Some of the variables causing results to be different were: pavement friction, driver skill, vehicle condition, and study procedures. Figure 5-1 depicts the results of braking studies conducted in Virginia and Alberta, Canada *(58)*. In these tests, all vehicles were kept in excellent condition by skilled mechanics. Tires and other equipment were relatively new, and drivers were carefully selected. Obviously, deterioration of any of these conditions would result in longer braking distances. These tests found that trucks operating in optimum conditions closely reflect braking distances used by AASHTO in design. Unfortunately, the real world situation is not usually this desirable.

In a recent study by Radlinski *(61)*, performance data were reported for vehicles in their newly manufactured condition with well-conditioned brakes. This performance should be similar to that which could be achieved on older vehicles if they are well maintained and equipped with original or equivalent braking system components. The author points out the two general methods used to test stopping distances. These are: 1) the panic stop with no limit on wheel lockup, and 2) driver modulated stops up to the point of lockup. In the first, the driver simply slams on the brakes, whereas in the second, he applies the brakes until a deceleration level is achieved which is just below lockup and holds that rate until the vehicle stops. The significant difference in the two types of tests is the stability control. This represents a legitimate concern in the real world where stopping conditions are almost never ideal. If the truck driver loses control due to locked wheels, the stopping distance will be greater than the test track results yielded by a straight skid. Therefore, the author maintains that the modulated stop is a more appropriate method to test a vehicle's ability to stop safely. Stopping distance tests used a long wheelbase three-axle bobtail tractor at 96 km/h (60 mph) to demonstrate the difference in braking distance. Using a dry pavement surface, the panic stop distance was 65.9 m (216 ft) and the modulated stop distance was 116.8 m (383 ft) *(62)*. This is an increase of 77 percent in braking distance.

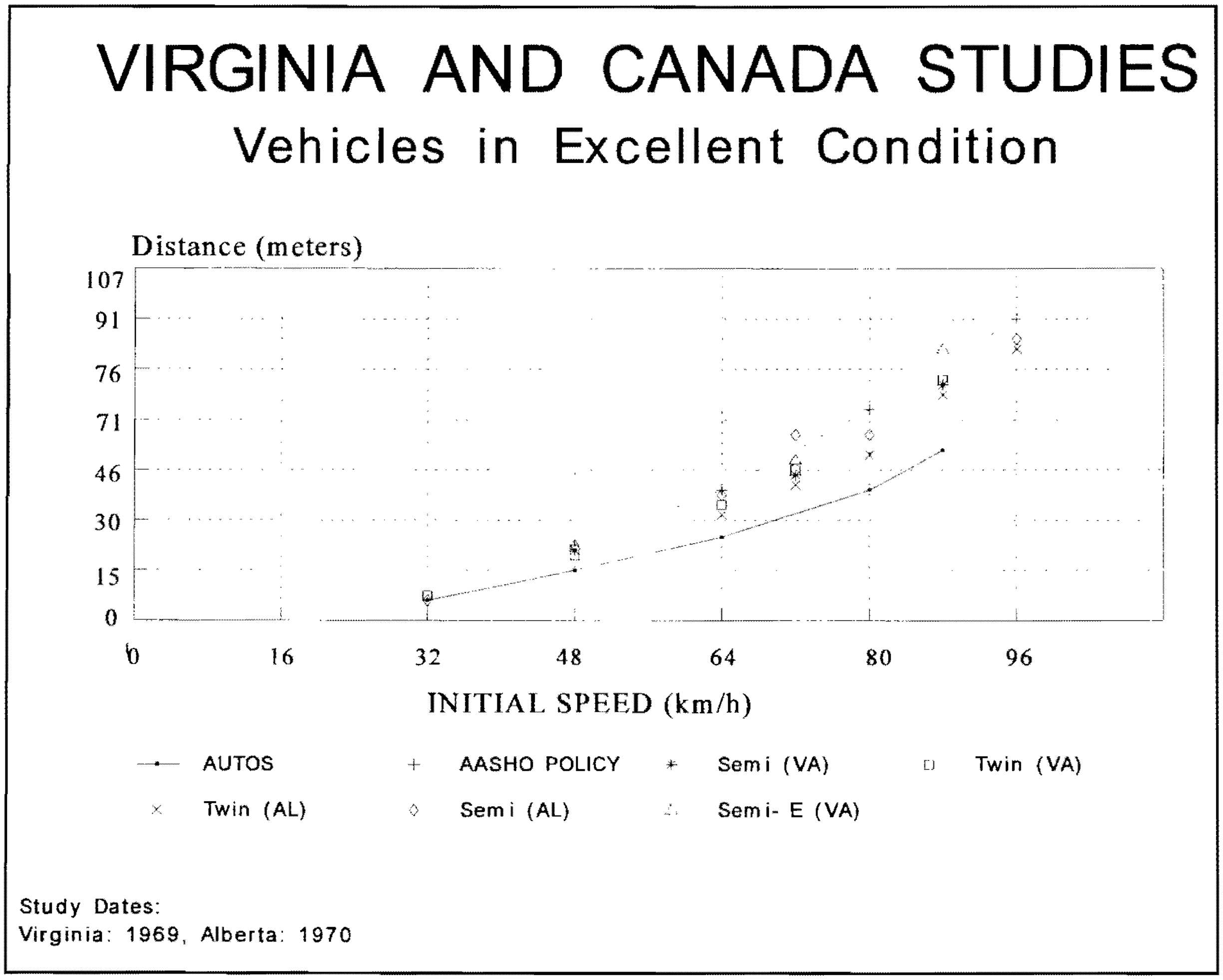


Figure 5-1. Early Braking Studies in Virginia and Canada

5.4.2 Less Than Optimum Conditions

Truck braking tests performed in Utah included other types of combinations, comparing double and triple combination vehicles with singles *(57)*. Tests were conducted on wet pavements and dry pavements with coefficients of friction of 0.64 and 0.92, respectively. Two series of tests were run -- the first used loaded doubles and triples at speeds of 32, 48, and 64 km/h (20, 30, and 40 mph). In the first series, there was little tendency for vehicles to jackknife on wet pavement. The triple appeared more stable than the double. Brakes were designed such that rearmost brakes locked before front brakes. The second series of tests added a single. The 64 km/h (40 mph) wet pavement test excluded the single due to its tendency to jackknife at 48 km/h (30 mph) on wet pavement. Triples again exhibited the ability to stop in a straight line on wet pavement. The overall conclusion was that triples were more stable than doubles, and they were both more stable than singles on wet pavements. For dry pavements, there was no observable difference in stability in the three vehicles. Triples required slightly more braking distance than doubles, and doubles required slightly more distance than singles.

Gordon *(59)* cites a study by the Bureau of Motor Carrier Safety in 1974 in which 1,200 trucks of various types were tested. Vehicles were randomly selected at weigh stations for testing. Braking distances measured were from brake pedal actuation at 32 km/h (20 mph) to full stop. According to Gordon, these results functionally relate to stopping distances at other speeds and on other roadway surfaces. Gordon plotted a cumulative frequency distribution of braking distances by vehicle type. Four vehicle types were compared: passenger cars, three-axle single unit trucks, an AASHTO 2-S2 vehicle, and a twin trailer combination vehicle. Gordon assumes the 2-S2 is representative of the 2-S1 and the 3-S2 vehicle.

From the cumulative graph, the 50th percentile stopping distances of all vehicles show an important relationship. For cars, this value is 6.63 m (21.75 ft), and for the three trucks represented, the average is 10.58 m (34.71 ft). From the corresponding deceleration rates, the ratio of deceleration rate of cars to trucks is 12.45/19.87, or approximately two-thirds. Likewise, the stopping distance ratio of cars to trucks is 21.75/34.71, or approximately two-thirds. This supports findings by Peterson *(57)* in the Utah studies and requirements in the FHWA "Motor Carrier Safety Regulations." These regulations require car deceleration rates of 6.4 m/sec^2 (21 ft/sec^2) and truck deceleration rates of 4.3 m/sec^2 (14 ft/sec^2). This car/truck ratio is again two-thirds. Acknowledging this relationship, one can modify the AASHTO equation.

$d = V^2/30f$ = Braking distance for passenger cars,

For truck braking distance: $2/3\ d = V^2/30f$, and

Thus: $d = V^2/20f$ This is the equation proposed by Peterson *(57)*.

Vehicle load is also a factor in braking distance. Figure 5-2 shows the stable stopping distances from 97 km/h (60 mph) on dry pavement for various types of air braked vehicles using this modulated stop technique. Also shown for reference is the stable stopping distance for a passenger car under similar conditions. Heavy vehicle data are from reference *(62)*; passenger car data are from references *(63,64,65)*. Buses perform well because their center of gravity is fairly low and their brakes are designed for loaded-to-unloaded conditions which are similar. Brakes on tractor-semitrailers (second bar from top), on the other hand, are optimized for the loaded condition. In the unloaded condition, they do not perform as well (fourth bar from top). Bobtail tractors exhibited the longest modulated stopping distances of any vehicle configuration and condition tested.

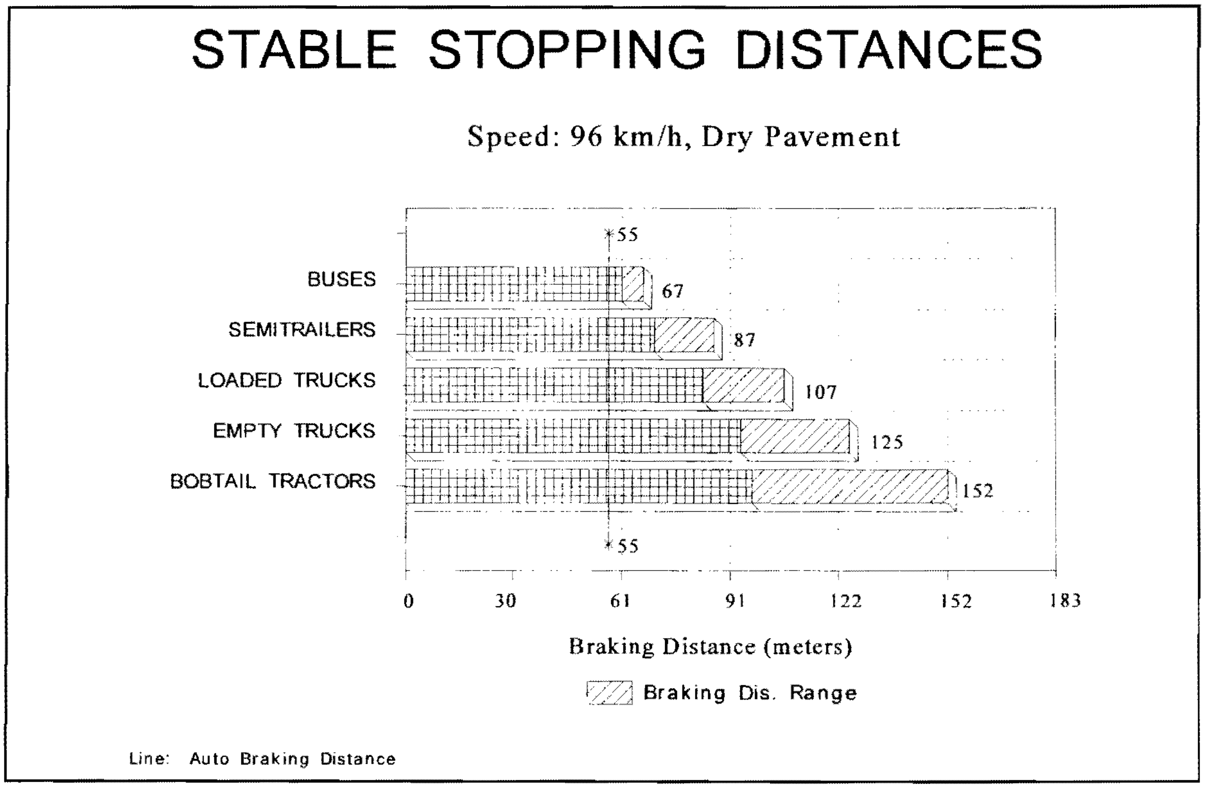


Figure 5-2. Stable Stopping Distances of Various Trucks

Another useful comparison is the current AASHTO braking distance, which assumes wet pavement (f = 0.29). For a design speed of 96 km/h (60 mph) the calculated braking distance range for passenger cars is 95 m to 126 m (311 ft to 414 ft). Using the same relationship developed by Peterson above, the design stopping distance for trucks on wet pavement would be 190 m (620 ft). This exceeds the detection limit currently used by TxDOT for 96 km/h (60 mph) approaches. This is a topic that warrants further investigation by the research community, especially with some at-grade signalized intersections with 112 km/h (70 mph) speed limits.

5.5. HUMAN FACTORS CONSIDERATIONS

The AASHTO Green Book driver reaction time for its stopping distance model is 2.5 seconds. However, this is probably excessive for an expected condition such as that existing at a signalized intersection. For purposes of this discussion, a value of 1.0 seconds is used. At a high- speed approach to an isolated intersection at, say 96 km/h (60 mph) driver reaction time adds another 27 m (88 ft) to the distance required for a vehicle to stop once the signal has changed from green to yellow.

The next logical step in the consideration of truck stopping distance is not necessarily what the minimum stopping distance would be, but what deceleration rate the driver will accept. So far, this discussion has assumed that the driver will accept a very high deceleration rate. For example, according to Figure 5-2 stopping distances, experienced drivers of tractor-semitrailers (3-S2) traveling at 96 km/h (60 mph) can stop within 91.5 m (300 ft), representing a deceleration rate of 4.0 m/sec^2 (13 ft/sec^2). One must realize that this is a high deceleration rate and one which is very uncomfortable. Automobile drivers are known to be uncomfortable at substantially lower deceleration rates, and truck drivers have reasons to limit their deceleration rates even more.

One reason for some truck drivers not stopping at intersections unless absolutely necessary is simply due to the delay and the slow acceleration characteristics of trucks. Delay costs are much higher than for passenger cars. There is discomfort to the driver, and there is a possibility of load shift and/or loss of control with articulated vehicles when extreme braking occurs. There is little information in the literature regarding deceleration rates of truck drivers, especially approaching isolated signalized intersections. Therefore, TTI conducted its own speed study of trucks approaching isolated intersections as part of this research. One of the studies occurred in Bryan, Texas on F.M. 2818 at Leonard Road and the other occurred on U.S. 290 near Mason Road just outside Houston, Texas. Both are isolated intersections. Because the F.M. 2818 site had few trucks in the desired speed range (over 80 km/h (50 mph)), only the U.S. 290 data are presented.

5.6 FIELD TRUCK SPEED DATA

Table 5-1 summarizes the truck speeds approaching the U.S. 290 intersection at relatively high speeds in cases where the signal indication changed from green to yellow to red as the truck neared the intersection. The difficulty of this process should be noted in order to explain reasons for limited data. Even though the number of trucks on U.S. 290 is high, only a few could be captured while the signal turned from green to yellow to red and which were unimpeded by other traffic. The methodology utilized two observers, one operated a hand-held radar gun and the other served as recorder. The field crew started by marking a total distance of 183 m (600 ft) from the stop line in 30 m (100 ft) increments. As decelerating trucks passed each point, the radar gun operator stated the speed. Not all trucks stopped at the onset of yellow; some increased their speeds to pass through the intersection on yellow and red. Some stopped successfully, but

Table 5-1. Speed Change with Onset of Yellow

	DISTANCE FROM STOP LINE											
Class	600	500	400	300	200	100	0	Loaded	Phase	Dir	Yellow	Comment
3s2	53	51	48	25			0		G-R	Thru		
3s2	50	47	31			0	0		G-R	Thru		
3s2		43	41	37	23		0		G-R	Thru		
3s2	41	49	51	50	50	50	50		G-R	Thru	200	
3s2		63	63	60	61	61	61		G-R	Thru	300	
3s2		39	38	31			0		G-R	Thru	700	
3s2	37	36	35	21	20		0		G-R	Thru	800	
3s2	52	51	38	35	20		0		G-R	Thru	500	
3s2	52						0		G-R	Thru	500	
3s2	52	52	52	53	54	54	53		G-R	Thru	100	
3s2	50	50	50	51		18	0		G-R	Thru	400	
3s2	41	40	37	30			0		G-R	Thru	1000	
3s2	55	61	62	65	65	62	62		G-R	Thru	300	
3s2	45	45					0		G-R	Thru	500	
3s2	47	46	46	47	48	51	52		G-R	Thru	800	
3s2	50	50	35	30			0		G-R	Thru	1000	
3s2	43	41	38		22	15	0		G-R	Thru	700	
3s2	52	52		29		0			G-R	Thru	1000	
3s2	56	50		33			0		G-R	Thru	700	
3s2	56	55	55				0		G-R	Thru	400	
3s2	50	51	50	51	51	51	51		G-R	Thru	300	
3s2	49		53	54	54	55	55		G-R	Thru	200	
3s2	50		39	27	24		0		G-R	Thru	700	
3s2	43	40	38	34	25		0		G-R	Thru	1500	
3s2	45	42	40	32	22		0		G-R	Thru	800	
3s2	55		35	32	21		0		G-R	Thru	700	
3s2		53	54	54	32	17	10		G-R	Thru	300	Ran Red
3s2	51	55	35				0		G-R	Thru	700	
Avg Spd	49	48	44	40	37	36	15					
Std Dev	5.15	6.79	9.15	12.7	16.8	24	24.5					
Lower CI	38.7	34.4	25.7	14.6	3.37	-12.1	-34					
Upper CI	59.3	61.6	62.3	65.4	70.6	84.1	63.9					

at least one was observed trying unsuccessfully to stop, running the red indication at a speed of approximately 16 km/h (10 mph). Of the trucks that decelerated approaching the intersection, none approached the possible deceleration rate of 4.0 m/sec^2 (13 ft/sec^2) calculated above. It should also be noted that the pavement was dry for all observed data. Truck driver characteristics are expected to change somewhat with wet pavement conditions.

The signal clearance interval must allow ample time for a truck to stop or to clear the intersection. For high speed approaches, this often requires an all-red phase to reduce the length of the yellow indication. The control logic that is used must consider truck driver characteristics under a variety of weather and lighting conditions to be successful. For trucks passing straight through the intersection, ending the green indication could be based on their speed and an acceptable deceleration rate. Turning trucks might need different considerations, depending on site geometrics and the existence of separate signal turn phases. Based on the data collected, truck drivers change speeds (either accelerating or decelerating) from as far away as 152 m (500 ft). All truck drivers except one, upon seeing a yellow indication at 91.5 m (300 ft) or closer, proceeded through the intersection. The one exception, already noted, attempted to stop but was unable to do so. This has implications for the detection system used for this study and the distance from the intersection where detection must occur.

Figure 5-3 is a plot of truck speeds from U.S. 290 at Mason Road. These speeds indicate that, for this intersection, with a posted speed limit of 88 km/h (55 mph) trucks began speed reductions at approximately 122 m (400 ft) from the stop bar. Because all data were collected in good weather daylight conditions and on dry pavement, it is recommended that inclement weather and darkness be included in future research. Additional data for this intersection are provided in Appendix A.

5.7 SUMMARY AND CONCLUSIONS

Results of stopping distance tests must be used with caution, paying very close attention to conditions of the test. Variables include: the load factor, wet versus dry pavement, vehicle configuration, maintenance levels of truck brakes, pavement coefficient of friction, control stops versus panic stops, and acceptable driver deceleration rates. In only a few of the tests which have been conducted have trucks exhibited stopping capabilities similar to passenger cars. Observed deceleration rates imposed by truck drivers approaching isolated signalized intersections are substantially lower than those found in the literature which documented panic or emergency stop conditions. It is apparent that under optimum conditions, large trucks can stop from 97 km/h (60 mph) in approximately 91.5 m (300 ft), although the TTI field data for speeds of 88 km/h (55 mph) do not indicate that truck drivers are willing to accept this high deceleration rate. Adding driver reaction time of 1.0 seconds to an appropriate braking distance of approximately 122 m (400 ft) requires that the front of a truck be no closer than 146 m (480 ft) to the stop bar when the yellow indication comes on. Determining the location of a detection system still requires adding the length of the design vehicle and an additional distance for the detector's processing time. Assuming 20 m (65 ft) and 0.2 seconds for vehicle length and processor time, respectively, detectors should be placed at a minimum of approximately 170 m (560 ft) for a design speed of 88 km/h (55 mph).

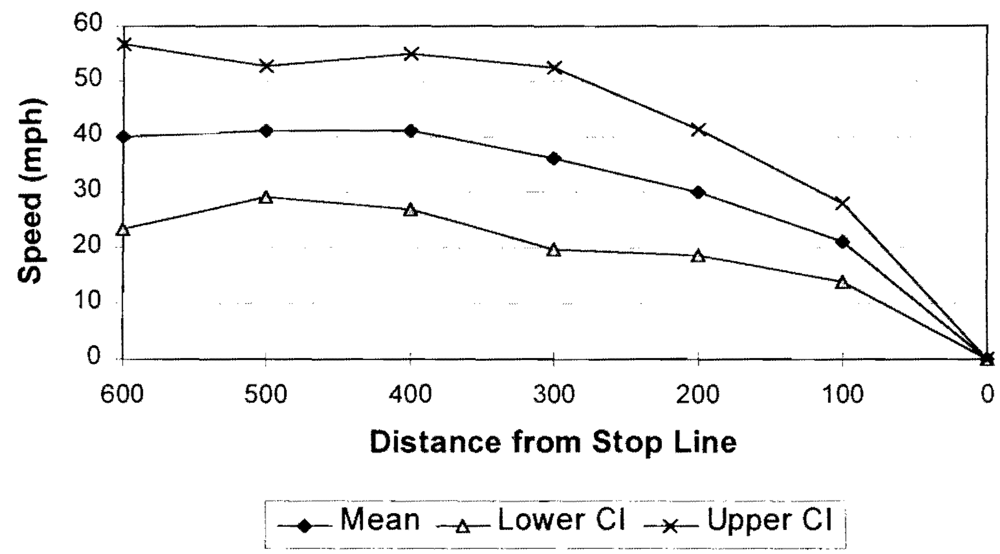


Figure 5-3. Speeds of Trucks With Onset of Yellow Then Red

6.0 SITE SELECTION AND DETECTOR INSTALLATION

6.1 INTRODUCTION

The process of site selection was twofold: selecting a site in the Bryan/College Station area for initial testing and selection of a site in the Pharr District. The criteria for site selection was similar for both, but the project team changed the "local" test plan in College Station because the requested location was unavailable. The ideal site would have the following characteristics: high volumes of trucks, high percentage of straight-through trucks, high-speed traffic, good sight distance, sufficient right-of-way, relatively new signal hardware, and either available space in the existing cabinet or more desirably, availability of a new cabinet. Of course the signal would need to be actuated with inductive loop or other detectors on the main street and side streets. The reason for high speed was to provide an adequate test for the selected technology. This assumes that high speed provides a more challenging environment than lower speed. Low side street volume was also desirable so that its increased delays would be minimized.

6.2 SITE SELECTION

6.2.1 Site Selection in Bryan/College Station

TTI staff searched the Bryan/College Station area for the best intersections for testing the truck detection system. The three that appeared to be best, according to the criteria stated above, were: F.M. 2818 at Leonard Road, F.M. 2818 at George Bush Drive, and F.M. 158 at the entrance to the Copperfield subdivision. The Leonard Road intersection had the most trucks so project staff selected it above the other two. Unfortunately, the city of Bryan did not approve a written request to use the intersection as a test site for detection of trucks and subsequently connecting to the traffic signal to extend the green phase to reduce stops to trucks. Therefore, TTI staff decided to utilize the TTI test site on S.H. 6 just south of University Drive (F.M. 60). The purpose of the initial test was to determine detection accuracy of the test systems, so it did not necessarily need to occur at an intersection. However, the second phase would need to utilize a traffic signal controller cabinet. Two options existed: 1) try again to locate an actuated traffic signal in the Bryan/College Station area, or 2) utilize a signal controller cabinet that was available in the TransLink™ Lab in the TTI building on the Texas A&M University campus. The latter option was chosen, with subsequent full scale tests in the Pharr District.

Figure 6-1 shows a layout of the test site on S.H. 6. The site was equipped with mounting hardware, power cables, and communication cables for mounting the Schwartz Autosense II overhead on the F.M. 60 bridge structure. The Bryan District of TxDOT gave approval for mounting bridge hardware, as well as installing pavement sensors for ground truth data. From its inception, TTI envisioned the site being used for testing these and other types of sensors in other research endeavors. Future site enhancements include the addition of a 12.2-m (40-ft) pole with mast arm to mount overhead and side fire detection equipment. There was no testing

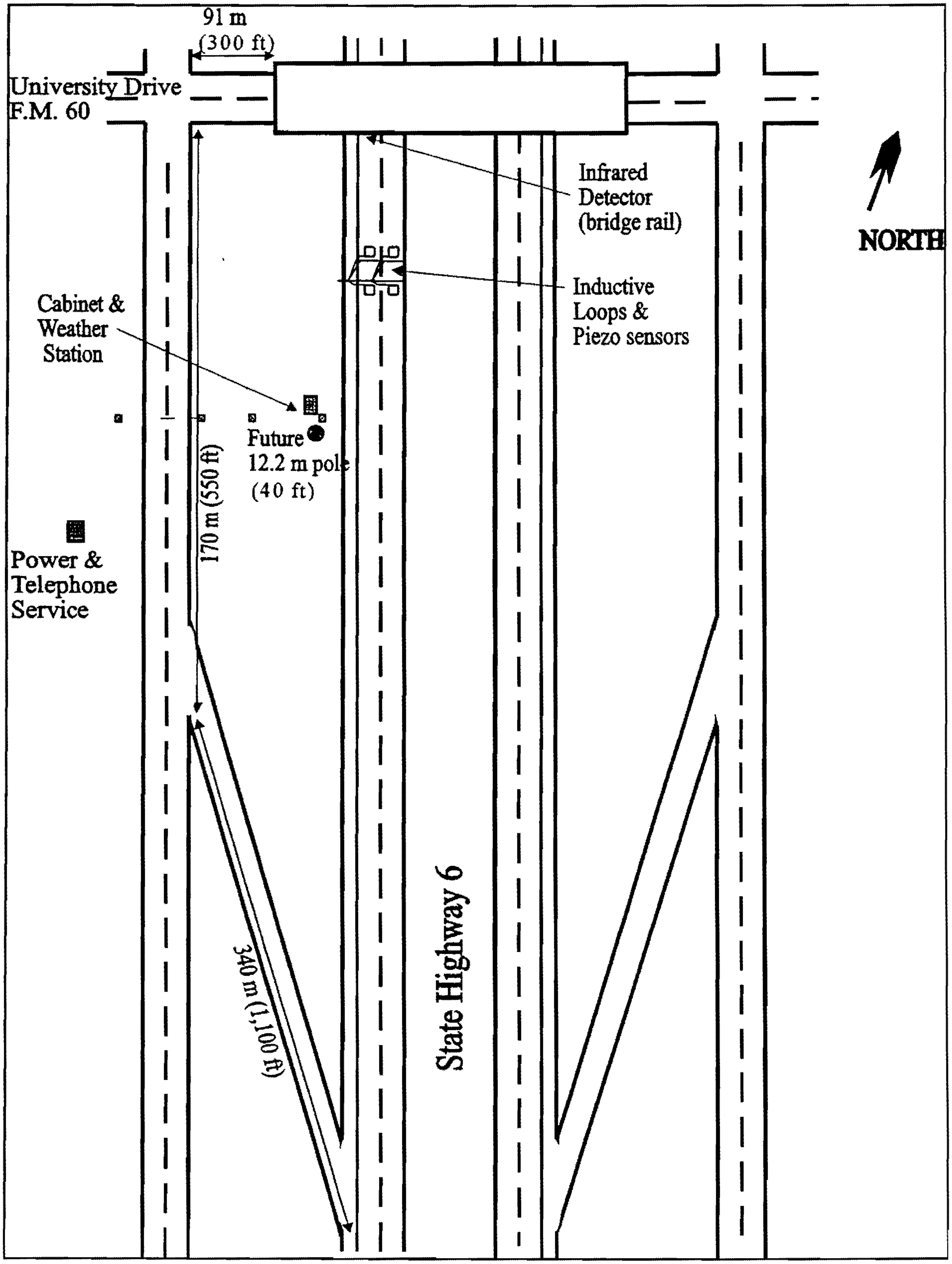


Figure 6-1. TTI Test Site in College Station

of the acoustic detectors on the bridge because their performance deteriorated due possibly to echoes. Therefore, TTI did the preliminary testing of the acoustic sensors by mounting them on a trailer equipped with a 9.1-m (30-ft) telescoping pole at a distance of 7.6 m (25 ft) from the roadway.

Figures 6-2 and 6-3 show the Autosense II mounting hardware and the detector's orientation with the detection area. The manufacturer's suggested mounting requires that the detector be practically vertical with respect to both the *"y"* and *"z"* axes. The exception is a five degree inclination toward approaching traffic. The setup in College Station adhered to this orientation. However, after consulting with the manufacturer, TTI opted for a non-vertical orientation in the Pharr District because the detector could not be centered over the lane.

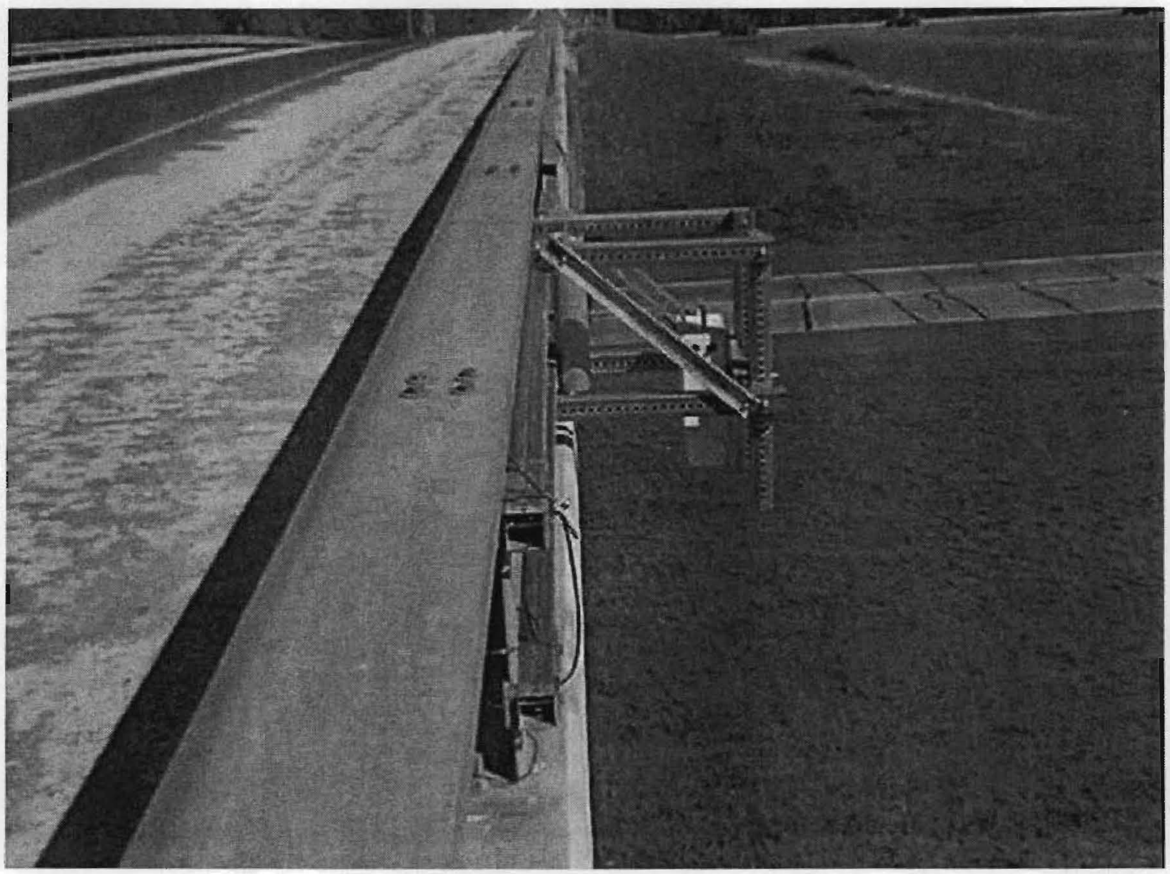


Figure 6-2. Side View of Autosense II

6.2.2 Site Selection in the Pharr District

Researchers evaluated numerous intersections for installation of the truck detection system in the Pharr District. Table 6-1 summarizes information pertaining to the primary locations evaluated. Some of these sites would have served the purpose of this research but they were scheduled for construction near the time of installation. As indicated, the intersection in Sullivan City was almost ideal. One negative aspect was its distance from the Pharr District office.

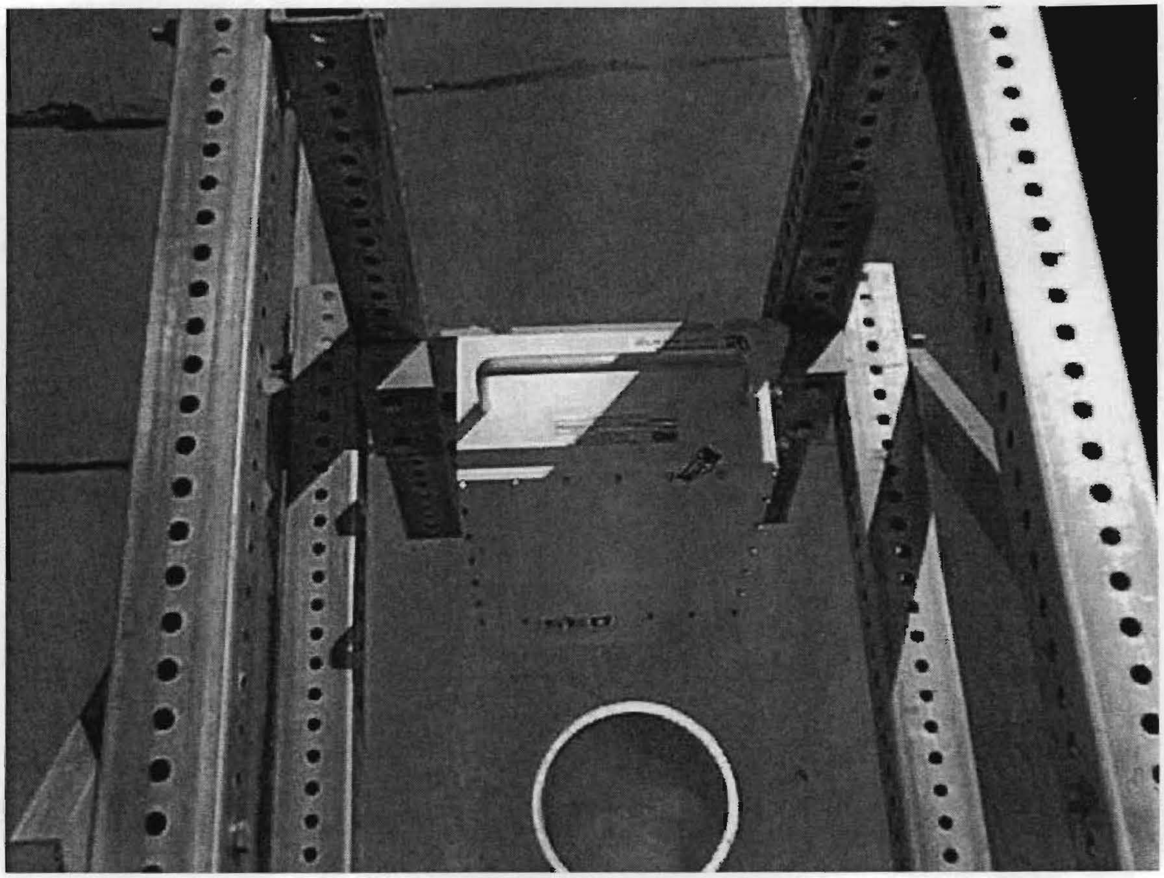


Figure 6-3. Top View of Autosense II

The Sullivan City site was best because it had high-speed approaches, clear right-of-way in either direction, high numbers of trucks, lower volume on the side streets than some other locations, and the traffic signal hardware was relatively new. Another example that was acceptable in many respects was F.M. 511 south of the Port of Brownsville. That intersection was not as appropriate because almost all truck traffic turned at that intersection. Eastbound trucks generally turn left and southbound trucks generally turn right. The airport is just west of the intersection, and the port is just north of the intersection. The east-west intersecting roadway is a five-lane curb and gutter section on the west side, narrowing to two lanes on the east side. F.M. 511 north and south of the intersection is a narrow two-lane asphalt roadway with no shoulders.

Sullivan City is a small community west of La Joya and west of McAllen on U.S. 83. Figure 6-4 shows its location with respect to other nearby communities. The route is heavily used by large trucks traveling between Laredo and the lower Rio Grande Valley. The selected intersection in Sullivan City is isolated from others; the closest signalized intersection in either direction on U.S. 83 is approximately 8 km (5 mi) away. The research supervisor proposed using the eastbound approach because the roadway is straight and level with good sight distance. Site improvements required installing a 6.1-m (20-ft) signal pole with a 13.4-m (44-ft) mast arm and two 1.8 m by 1.8 m (6 ft by 6 ft) inductive loop detectors in each lane at a distance of approximately 168 m (550 ft) from the stop bar. Other smaller improvements included new cable pulled through existing conduit, a telephone line, an additional cabinet (shortly after other components were installed), and a short section of new conduit.

Table 6-1. Intersections Evaluated for Detector Testing

Route	Location	Comment
U.S. 281/U.S. 281	At Pharr International Bridge	Slow traffic but high truck volume
U.S. 281/F.M. 1015	Progresso International Bridge	Few trucks
U.S. 281/F.M. 509	Los Indios International Bridge	Most trucks turning
U.S. 281/Spur 241	Hidalgo International Bridge	Slow speeds, many trucks turning
F.M. 1016/S.R. 115	International Trade Zone	Construction planned
F.M. 1016/S.R. 336	International Trade Zone	Construction planned
F.M. 511	South of Port of Brownsville	Most trucks planned
U.S. 83/F.M. 2360	La Grulla	Construction planned
U.S. 83/F.M. 886	Sullivan City	High truck volume, few turning trucks, high speeds, and low side street traffic

6.3 DETECTOR INSTALLATION

The installation of detector systems requires basic infrastructure to support the continued uninterrupted operation of non-intrusive detectors. This includes power and communication support as well as a stable mounting structure that does not compromise the accuracy and longevity of the detector. Care must be exercised in designing and fabricating these support mechanisms in order to get optimum performance from non-intrusive detectors. It should be understood that detection results are highly site-specific and labor intensive. Optimum results are heavily dependent upon spending many hours utilizing perhaps repeated cycles of monitoring and adjusting, then continued monitoring and re-adjusting. With new products, manufacturer technical support does not always know critical answers either, because the product has not been fully tested. Appendix C is an Operations Manual that can assist the installer in this process.

TTI experienced problems installing the two detector systems in both College Station and Sullivan City. One weakness of both detectors was not being built for the rugged environment of field installation. Not all of the problems should be associated with the sensors, however, because TTI personnel were initially unfamiliar with them. Some problems resulted due to simple wire splices or other connections that were difficult to diagnose due to the aforementioned unfamiliarity.

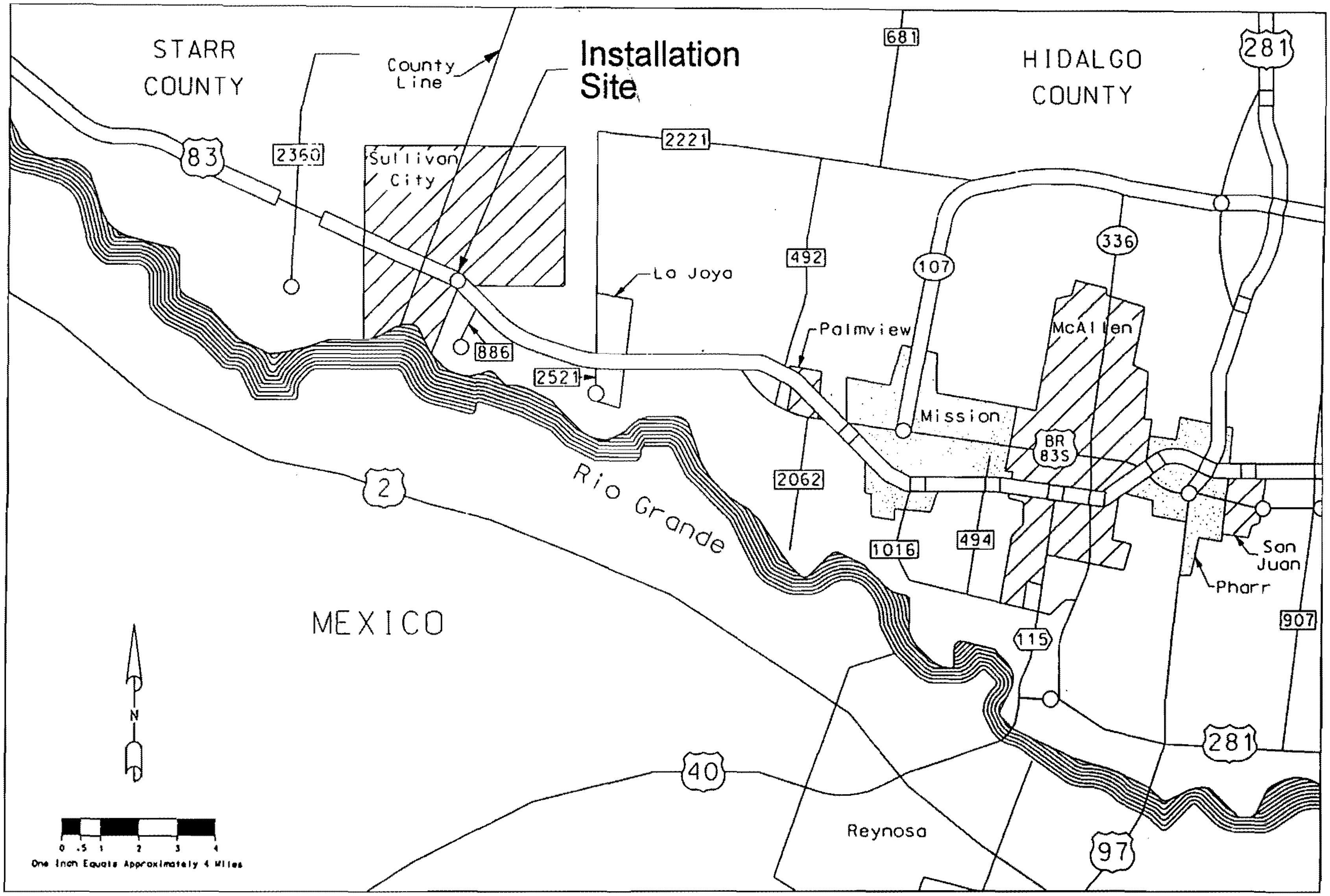


Figure 6-4. Area Map

Testing of new sensors also requires a system to verify their operation. Two basic means were available during this research. One verification method was recorded videotape with subsequent playback and observation; the other method utilized a vehicle classifier as "ground truth." The typical scenario first affirms accuracy of the ground truth method (in this case the classifier). Once established, the ground truth method provides baseline data for determining the accuracy of each new detector. Data comparisons included speeds, vehicle counts, and vehicle classification. Comprehensive testing requires varying light and weather conditions. Other elements that should not be overlooked include difficulty of set-up, reliability once installed, and difficulty of continued operation and modification.

6.3.1 Installation Requirements for the SmartSonic Detector

The SmartSonic Traffic Surveillance System (TSS-1) utilizes sound energy originating from a vehicle (including tire noise) for vehicle detection. The TSS-1 system uses variations of sounds generated by different vehicles to detect presence, speed, and classification of passing vehicles. The sensors are comprised of a microphone array which detects the sound energy emitted from the point of interest in the travel lanes. Each lane requires its own sensor.

Optimum performance of the sensors requires that they be mounted above and adjacent to the roadway. Suggested mounting heights range from 6.1 m to 10.7 m (20 ft to 35 ft) above the roadway. Each sensor should be oriented to detect the noise generated at the point of contact between the vehicle and its travel lane. Suggested pointing angles for the sensors range from 10 to 40 degrees off vertical. The sensors also perform better if not placed directly over the lane. Up to four sensors may be used with one controller unit.

The TSS-1 controller is programmed with a personal computer using terminal or hyper terminal software. The user must connect the controller to the sensors through a small transition module which may be mounted to a cabinet. All data communication and power are transmitted through the 22 gauge cable connecting the sensors, transition module, and controller. The conductor wire specification is dependent upon the number of sensors communicating with the controller. The controller requires 120V AC in the cabinet, whereas sensors need 24V DC. When monitoring more than one sensor, the user must set the detector prior to beginning data collection to assign lane numbers to each one. Once the sensors are properly identified, the controller can output data for each detection point and then these data can be processed accordingly.

TTI researchers installed two TCC-1 sensors in Sullivan City, Texas. Sensor one monitored the outside (right) lane of travel and sensor two monitored the inside lane. TTI staff set these identifications in the office and labeled them before installation. Technicians connected the sensors in series at the site, such that home run cable communicated between the two sensors and the controller from sensor two. Each of the sensors was mounted 6.1 m (20 ft) above the travel lanes at an angle of 28 degrees off vertical. The home run cable connected the controller cabinet, a distance of approximately 244 m (800 ft) downstream from the detection area. Installers used Astro-Brac Cable Mount Clamp Kits to mount the sensors to the pole's mast arm.

The transition module and the controller were mounted inside the cabinet and the controller connected to an Industrial Computer for data collection and processing. This computer may be used to send a phase hold signal after processing the data transmitted from the TSS-1 system.

6.3.2 Installation Requirements for the Autosense II Detector

The Auto-Sense II is a self-contained non-contact vehicle detection sensor. This sensor operates above the lane of travel, utilizing a scanning laser rangefinder to measure three-dimensional profiles of vehicles as they pass directly underneath the sensor. The sensor processes these profiles directly within the sensor and outputs data through its serial port. The system scans two narrow beams at a fixed angular separation after the rangefinder measures the sensor mounting height. With the measured height and a fixed angular separation of the beams, it measures speeds and utilizes an algorithm for vehicular classification. Each sensor is self-calibrating and does not need to be programmed for data output. Data are continually output through the serial port.

The sensor is generally mounted centered over the lane of travel. It should be mounted such that beam one is detected before beam two. This means the sensor is typically mounted on the upstream side of the mounting structure. It should also be mounted angled 5 degrees off vertical (toward approaching traffic) at a height of 5.5 m to 7.6 m (18 ft to 25 ft) above the lane of travel. Minor structure vibrations do not affect sensor performance. The sensor requires four conductor 22- gauge wire for data communication and 120 volt AC. The system uses a LDM70 Dataforth modem for communication between sensor and controller. The vendor provides software for user-defined output format, but the sensor will output to the computer without the software using the appropriate protocol. Once the sensor is in place, the communications may be verified from the LED indications shown below on the LDM70 and software.

The following pertains to the AS2TEST.EXE software program developed by TTI:

- Verify that the latest version AS2TEST.EXE is being used (VER 1.01.26 as of 6-23-97).
- Select the correct serial port from the configure software section (COM1 or COM2).
- Select the baud rate to be 57.6.
- Execute the "Save PC configuration" to save this setup.

The following pertains to the LDM70 modem utilized by the Autosense II detector:

- When properly connected, the TD and RD LED indicators will most often be **OFF**, coming **ON** momentarily during the passage of a burst of data.
- See attached LDM70 installation instructions for more details.

- DTE / DCE Switch setting: When using a standard straight-through Com cable - set switch to **DCE**. See Table 6-2.

Table 6-2. Switch Settings for the LDM70

LED Indicators	• Normal Operation	• RX+ or RX- Open circuit	• DTE - DCE • switch setting wrong	• TX+/- and RX+/- swapped
RLSD	• ON	• OFF	• ON	• OFF
• RD	• OFF	• ON	• OFF	• ON
• DTR	• ON *	• ON *	• ON *	• ON *
• TD	• OFF	• OFF	• ON	• OFF

* OFF when using a serial cable without DTR.

TTI staff and TxDOT installed an Autosense II sensor at the selected intersection in Sullivan City. It should be noted that site constraints required modification in the orientation of the sensor. Because the mast arm was not long enough to place the sensor over the center of the lane as desired, installers had to seek assistance from the manufacturer. The sensor had to be mounted on the inside edge of the outside (right) lane and angled approximately 15 degrees off vertical. This angle was required to ensure the detection of only one lane with full lane coverage. The sensor mounting height was 6.1 m (20 ft).

The installation crew used 12 gage wire for power connection between the controller cabinet and the sensor. Data communication used shielded cable with four conductor 22 gage twisted pair. As with the other sensors, this detector communicated with an industrial computer placed inside the cabinet. Finally, installers reviewed the checklist prior to starting the sensor communicating and fully utilizing the TTI software using the system's serial protocol. The site computer stored data being sent by the detector via the LDM70 modem for later download and evaluation.

6.3.3 Detector Installation in Bryan/College Station

The TTI test site on S.H. 6 in College Station facilitated the initial testing. The F.M. 60 bridge provided the support structure for the Autosense II infrared detector. TTI had installed power and communication cables and mounting hardware for this installation in other research activities. Therefore, all that was needed was an additional bracket for mounting the sensor to the bridge hardware. Because the acoustic detector performed better on a pole near the roadway than on an overhead bridge, TTI utilized one of its portable detection trailers to test the acoustic sensor at the test site. This method too was problematic because aiming the detector was difficult with the telescoping pole. Research technicians calculated the necessary vertical angle with the detector within their reach from ground level then raised the pole to the desired height. This method was inexact, requiring a few trials to achieve the detector's best performance. TTI was unable to get reliable performance from either the speed or the classification algorithms while testing continued at the S.H. 6 location. In fact, thorough testing of this detector did not occur until near the end of the project while final testing occurred in Sullivan City.

6.3.4 Detector Installation in the Pharr District

Installation of the new hardware was a joint effort between TTI and the Pharr District. The district installed the pole, inductive loops, and cabinet, and pulled cable through the conduit. TTI brought the acoustic and infrared detectors and other truck detection hardware to the site and installed them once the pole, mast arm and other hardware were installed. TTI and the district followed the following steps (not necessarily in order) in accomplishing the site installation: 1) install pole base and allow concrete to cure for a minimum of seven days, 2) run cable from the existing cabinet to the pole, 3) install new cabinet for new detector components, 4) install pavement inductive loop sensors, 5) install the pole on the base and bolt on the mast arm, 6) install infrared and acoustic sensors on the mast arm, and 7) install and hook up the classifier for test of data being generated by the infrared and acoustic sensors. TTI personnel made necessary adjustments to height, offset, or aim of non-intrusive systems to optimize performance. After testing for a relatively short period of time on site, project staff left all systems running to collect data for several days to determine truck detection accuracy of all systems. The purpose of this data collection was to subsequently compare data to determine which of the two non-intrusive system(s) would be accurate enough to detect trucks and extend the green indication.

The district utilized existing conduit in the median of the roadway because it had sufficient capacity for pulling new wire to the cabinet. Because the median had sufficient width and because of the conduit location, the district placed the pole in the median instead of on the outside. This pole placement meant that the mast arm extended over the left lane as vehicles approached the signal at F.M. 886. Because most trucks approached in the right lane, the infrared sensor was oriented to detect the right lane. There were two acoustic detectors, one for each lane. Figures 6-5 and 6-6 show the two acoustic detectors nearer the pole and the one IR detector mounted at the extreme end of the mast arm. Even though the typical orientation of the IR sensor is vertical, TTI opted for a non-vertical orientation in the Pharr District because the detector could not be centered over the lane. The end of the mast arm was approximately over the lane line (separating the two lanes). The sensor was rotated in a plane perpendicular to the direction of vehicular traffic on the roadway.

6.4 CONSIDERATIONS IN PLACING THE POLE

Chapter 5 provides information on observed stopping distance requirements for trucks. Based on observed stopping characteristics of trucks at an intersection near Houston with similar approach speeds and information in the literature, the detection system had to be placed far enough back to allow the truck to proceed safely or to stop safely. If the truck is forced to stop, the distance must be sufficient to allow the vehicle to clear the detectors, provide the driver with reaction time, allow system processing time (classify the vehicle and send the green extension), and provide reasonable deceleration distance. If the truck is allowed to proceed, the time must be sufficient to get the truck close enough to the intersection that the complete vehicle clears the stop bar on yellow.

It is apparent that under optimum conditions, large trucks can stop from 97 km/h (60 mph) in approximately 91.5 m (300 ft), although the TTI field data for speeds of 88 km/h (55 mph) do not indicate that truck drivers are willing to accept this high deceleration rate. Adding driver reaction time of 1.0 seconds to an appropriate braking distance of approximately 122 m (400 ft) requires that the front of a truck be no closer than 146 m (480 ft) to the stop bar when the yellow indication comes on. Determining the location of a detection system still requires adding the length of the design vehicle and an additional distance for the detector's processing time. Assuming 20 m (65 ft) and 0.2 seconds for vehicle length and processor time, respectively, detectors should be placed at a minimum of approximately 170 m (560 ft) for a design speed of 88 km/h (55 mph).

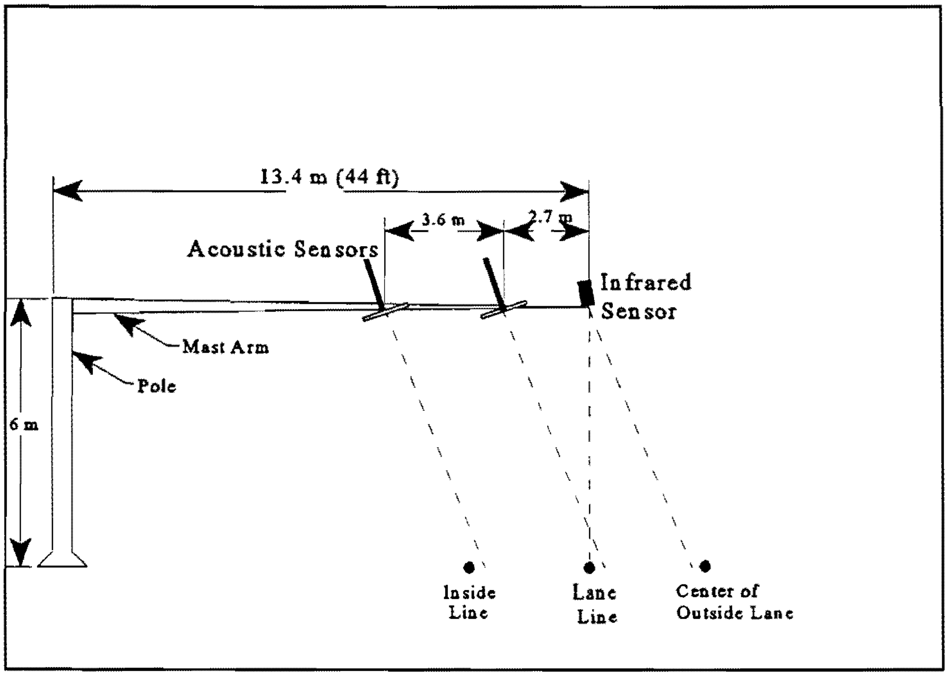


Figure 6-5. Approach View of Pole and Mast Arm With Detectors

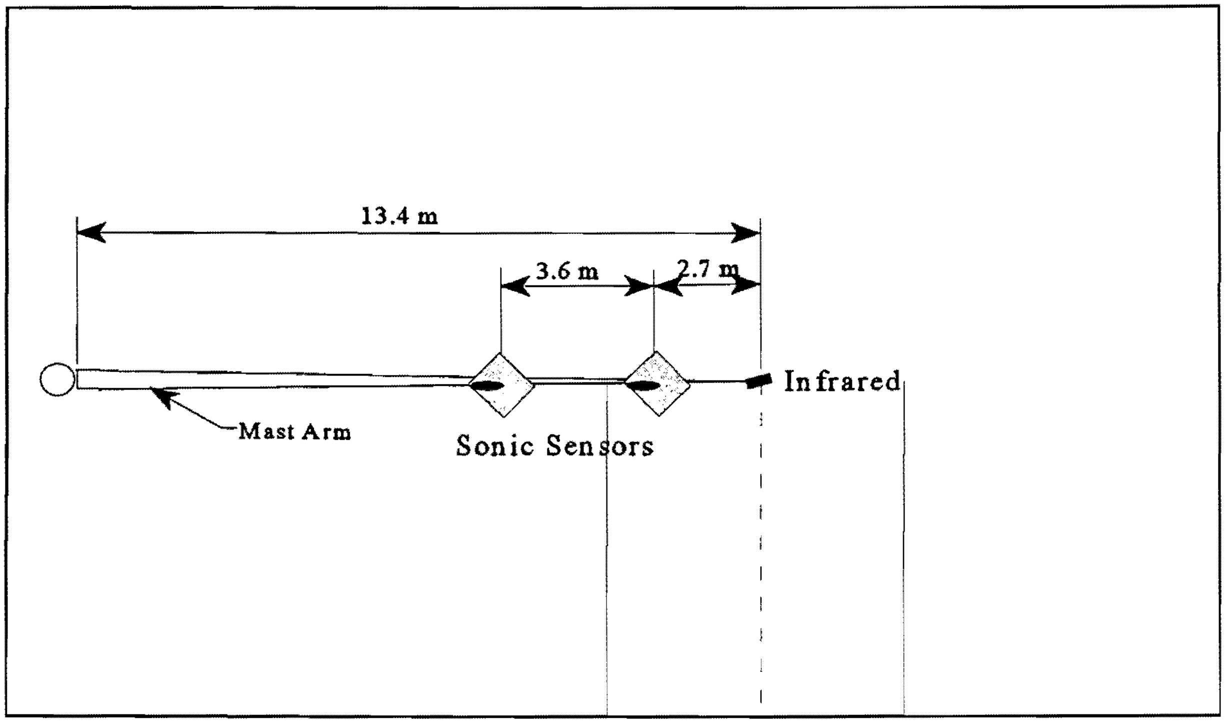


Figure 6-6. Top View of Pole and Mast Arm With Detectors

According to the *Traffic Detector Design and Evaluation Guidelines* by Bonneson et. al. *(66)*, the "dilemma zone" for a 88 km/h (55 mph) design speed extends from 76 m (250 ft) to 119 m (390 ft) from the stop line. By definition, there is a 90 percent probability of drivers stopping if presented a yellow indication at 119 m (390 ft). It is unclear whether the data included truck drivers, but these findings appear to support data observed on U.S. 290 using only trucks.

If truck drivers are provided a green extension, it should be of sufficient length to get them at least to the end of the dilemma zone (10 percent probability of stopping). The length of the green extension at 88 km/h (55 mph) must therefore allow the front of the truck to reach a point which is 76 m (250 ft) from the stop line. Therefore the onset of yellow could occur at the design speed 3.7 seconds later and the likelihood of a truck driver trying to stop would be remote. This yellow time should be rounded up to 4.0 seconds. As noted before, at a slower speed, the travel time would be longer from point of detection to end of dilemma zone. For example, at 72 km/h (45 mph), the end of the dilemma zone would be at 48.8 m (160 ft) from the stop line. The green extension must be sufficient for the truck to continue at a constant speed for a distance of 89 m (292 ft), requiring 4.4 seconds. Rounding up to the nearest half second, the green extension would be 4.5 seconds.

7.0 FINDINGS

7.1 DETECTOR INSTALLATION

Installation of detectors in the Pharr district in Sullivan City was a joint effort between the district and TTI researchers. The district installed the pole with mast arm, the inductive loop detectors, a new cabinet, and pulled cables through existing conduit for power and communications between the pole and the cabinet. Once the basic hardware was in place, TTI transported infrared and acoustic detectors to the installation site and installed them on the pole mast arm. This required aiming and testing the systems and extensive troubleshooting. The district made one of its bucket trucks available for installation and aiming of the detectors.

7.1.1 Sensor Installation Problems

Once the detectors were installed on the mast arm, TTI tested all wiring for communication and transmission of both power and data. Initial problems with communications between the pole and cabinet were thought to be associated with the eight-pair twisted shielded cable. When this cable was ordered, it was not available in a long enough length to extend the full 244 m (800 ft) needed to connect the pole and the cabinet without a splice. When TxDOT installed this cable, it was spliced and pulled through the existing conduit for subsequent connection by TTI. Therefore, researchers suspected that the splice at mid-length might be the problem. They tested all wire connections as well as detector functionality at the pole. If indicator lights on the detector were illuminated upon vehicle passage, the detector was at least detecting vehicles. If the same signal was not received at the cabinet end of the cable, then further testing on that end ensued. It should be noted that preliminary testing of the infrared detection system in College Station was successful, leading researchers to focus on data transmission cables and anything else that was different for this set-up than in College Station. Initial testing of the inductive loops only required sorting wires to pair them properly then testing them by hooking up to the classifier.

The LDM70 modem, which is a critical component of the Autosense II infrared sensor, developed a problem at one of the terminal strips. The strip came loose from the board and the proper LEDs (Light Emitting Diodes) on the LDM70 were not active. This problem could only be detected after all of the wiring had been checked thoroughly. Because this modem is a specialty item and unavailable from local suppliers, installers decided to solder the wire directly to the board connection and bypass the terminal strip. Upon reconnecting wires to the sensor's home run cable, installers were able to test the sensor's output at the cabinet end of the cable.

The SmartSonic system measures sound generated by passing vehicles and utilizes this measurement to calculate speed and to classify vehicles as they pass through the detection zone of each sensor. Communication problems with the acoustic system became apparent after the final installation of the system controller. Initial attempts to connect the controller to communication port five of the computer and to communicate using serial protocols failed. This failure prevented information gathering and programming of the acoustic system. The second attempt switched to port three. This allowed the Windows based Hyperterminal software to access the controller and made communication with the acoustic system possible.

TTI programmed the controller from its remote location in College Station, Texas. This setup included dates and times, followed by the proper configuration required to retrieve individual vehicle records, which was later compared with the infrared and loop based systems already operating at the location. Future research efforts should further investigate communication using only serial protocol to set up and retrieve data from the SmartSonic Acoustic System.

7.1.2 Computer Interface Problem

TTI researchers experienced a problem with its software program both in College Station and in Sullivan City when the industrial PC was retrieving data from the TCC through one of the computer's serial ports. The industrial PC system would altogether cease functioning shortly after midnight on a daily basis. The TTI research team checked their software in attempt to isolate the problem. One possibility that was initially considered related to the software program closing the logfiles for every monitored sensor at midnight, then opening new files for the new day. To check this possibility, team members simulated the end of the day on the PC several times by changing the PC date and time. The software program closed the logfiles and started new logfiles for the sensors, including the TCC, successfully. However, when TTI simulated the end of the day on the TCC by changing the date and time in the TCC, the PC system would again cease its operations shortly after midnight. One hypothesis is that the TCC classifier processes the day's data just after midnight, causing it to hang up. Researchers contacted the manufacturer, IRD, to learn what the classifier is programmed to do at midnight. As of the September 1997, IRD engineers were still working to solve the problem.

7.2 USER FRIENDLINESS

7.2.1 The Autosense II Infrared System

After proper installation and hook-up, the infrared classification system requires little or no user adjustment. The software supplied by the manufacturer provides several formats for the sensor's output data and is not needed for calibration and configuration of the infrared sensor. TTI technicians installed later versions of the vendor's software, but these had application to the computer interface and not the sensor itself. Installing these software upgrades was a simple patching process from a personal computer. These upgrades proved to be beneficial for both data collection and communication by the sensor.

The LDM 70 modem that is part of the Autosense II system has several LEDs that assist the user in the set-up and troubleshooting processes. As noted in Section 7.1, checking these functions was critical to the performance of the system. The manufacturer also provides a means of checking the functionality of the entire detector system in the office prior to going to the installation site. One shortcoming of the LDM 70 is its lack of ruggedness, leading to the need to exercise extreme care in handling and hook-up.

7.2.2 The SmartSonic Acoustic System

TTI technicians checked the functioning of the SmartSonic acoustic detection system in the office by connecting its components and shaking a set of keys in front of the sensors. If the sensors were working properly, LEDs on the controller activated upon sound detection. It is very important that the installer pay careful attention to these LEDs because they indicate whether the sensors are communicating properly with the computer. Another precaution should be taken when installing the transition module, which must be handled carefully because the connected wires may easily overstress the connection terminal. The acoustic system can be tested and configured using the Hyperterminal software in Windows™ 95. The Hyperterminal software can also be used to view the sensor's output data for detected vehicles. The SmartSonic system can be configured to store data for detected vehicles in its memory and the recorded data can be downloaded at a later time. However, if the controller loses power, all data collected to that point will be lost. Only the setup for data collection will be kept in the memory. The retained setup is beneficial for restarting data collection.

7.2.3 The TCC Classification System

The TCC classification system was the easiest unit to operate of the three tested in this research. It is designed with numerous user-friendly features and can operate in an autonomous mode without other micro-processor based equipment. However, the TCC must use a computer interface to download stored data for conversion and office use. The software provided by the manufacturer allows up to four communication ports for connection to the classifier.

7.3 DATA ANALYSIS FOR SULLIVAN CITY

7.3.1 Frequency Comparison

Researchers monitored the TCC and infrared detectors from College Station via telephone line. However, it should be noted that this remote monitoring was much less efficient than originally anticipated due to power failures, noisy telephone service, and other possible problems that were never fully confirmed. TTI had monitored the same systems in College Station (see chapter 3) via telephone line with virtually no problems from power or telephone service. Effective transmission of data over telephone lines requires much better quality of service than voice.

TTI collected and stored data from the detectors in the industrial computer at the Sullivan City location over a time period of several days for the same lane. In the analysis which follows, lane one data are treated separately from lane two data simply because of the detector layout (see chapter 6). Lane one (the right lane) was monitored by the TCC, the infrared, and the acoustic sensors. Lane two only had the TCC and the acoustic detectors. In the data collection chronology, TTI collected data from lane one first with only the TCC and the infrared sensors, while other efforts focused on connecting with the acoustic detectors. Upon successfully downloading data from the acoustic detectors a few days after lane one data became available, additional comparisons of all three detectors became possible. Therefore, the data results are ordered first in lane one comparisons of only the TCC and infrared detectors, followed by both lane one and lane two comparisons of the TCC, the infrared, and the acoustic detectors.

The software, PC Anywhere, facilitated many of the functions necessary between College Station and Sullivan City. TTI was able to access the computer at the remote location for simple monitoring of detectors, as well as to transfer files, "reboot" the remote system, and reconfigure programs on the remote system. After transferring files via telephone lines to a computer in College Station, TTI researchers imported data into a statistical analysis program for sorting, analyzing, and sending output into readable ASCII files.

Again, the two systems initially compared in lane one were the Autosense II and the TCC system using inductive loop detectors (ILD). Comparing vehicle counts, or "frequencies," indicates system operational consistency and reliability compared to other systems. For example, comparison of large truck frequency at the monitored site constituted comparison between the infrared sensor and the TCC classifier in lane one. Results indicate little difference between the number of vehicle counts measured by each of the two operating systems. General observation indicates that the infrared sensor detected more trucks than the ILD system.

Table 7-1 provides a vehicle count comparison of trucks and non-trucks for three days when matched vehicle sets were available. In other words, there were data available for the same time period during which vehicles could be "matched" for both the TCC classifier and the infrared detector. For every one-hour period counted on July 25, the Autosense II (AS2) counted more trucks and non-trucks than the ILD system. Based on previous experience in College Station, the AS2 detector was very accurate on classification and probably more accurate than the TCC system, even though the TCC was originally intended to serve as the "ground truth" system. This is not to say that there were no errors in the AS2 output, but that they are less likely than in the TCC output. July 26, 1997 data indicate fewer trucks in the traffic stream as one would expect for the hours represented, 8:00 p.m. to midnight. For this sample of data, the Autosense II counted fewer trucks than the TCC system (by only three) but a larger number of non-trucks when compared to the TCC. The data for August 4, 1997 indicate that, again, the AS2 counted more trucks and non-trucks than the TCC system. The data show that there were approximately 7 percent more trucks counted by the AS2 than the TCC.

7.3.2 Speed Analysis

For the four days of data summarized by Tables 7-2 and 7-3 in which speeds are compared, the Autosense II sensor speeds were always higher, indicating a bias in the detector's speed output. In this case, the TCC is viewed as more accurate, with speed typically unbiased.

The TTI software is designed for the infrared system to classify vehicles first based on height and second on length and width. The TCC system only has the capability of classifying vehicles based on length. The length algorithm relies on the detected speed, so if the speeds are biased on the high side, the lengths will be biased on the short side. The AS2 and TCC sensors measured the data summarized in Tables 7-2 and 7-3 for trucks and non-trucks, respectively. Both means and standard deviations of AS2 data are larger in magnitude than that of the TCC.

Table 7-1. Lane 1 Counts of Matched Data

Date	Hour	TCC Classifier		Autosense II	
		Trucks	Non-Trucks	Trucks	Non-Trucks
7/25/97	10	19	281	24	287
	11	32	262	34	265
	12	26	290	30	297
	13	36	247	41	252
	14	29	236	42	240
7/26/97	20	2	192	2	200
	21	6	153	4	166
	22	0	114	0	125
	23	5	99	4	101
8/4/97	18	24	220	25	232
	19	15	171	19	174
	20	16	155	16	163
	21	13	126	15	128
	22	9	93	8	100
	23	10	57	9	56
SUM		242	2,696	273	2,786

Larger mean speeds reflect the aforementioned speed bias. The larger standard deviations reflect more spread or scatter in the AS2 data as compared to TCC. Means for truck speeds are 11 km/h to 16 km/h (7 mph to 10 mph) faster for these selected AS2 data, reflecting its speed bias compared to the TCC. For non-trucks, the range in sample means between the two detection systems is smaller, at 5 km/h to 6 km/h (3 mph to 4 mph), but the bias is still in the same direction. Standard deviations for the AS2 are still larger than for the TCC. It should also be noted that, in both tables, there are inordinately high speed values generated by the AS2 detector. These need to be verified by additional monitoring at the site as opposed to remote monitoring.

Table 7-2. Speed Comparison for Trucks Only in km/h (mph)

Date	Hours	Sensor	Obs.	Min.	Max.	Mean	Std.Dev.
07/25/97	10-14	IR	171	48(30)	125(78)	79(49)	15(9)
		TCC	142	43(27)	100(62)	68(42)	11(7)
07/26/97	20-23	IR	10	63(39)	98(61)	80(50)	12(8)
		TCC	13	54(33)	79(49)	67(41)	9(6)
07/27/97	12-20	IR	44	56(35)	146(91)	83(52)	18(11)
		TCC	49	45(28)	90(56)	67(42)	10(6)
08/04/97	18-22	IR	117	45(28)	188(117)	82(51)	21(13)
		TCC	109	41(26)	93(57)	68(43)	12(7)

Table 7-3. Speed Comparison for Non-Trucks in km/h (mph)

Date	Hours	Sensor	Obs.	Min.	Max.	Mean	Std.Dev.
07/25/97	10-14	IR	1341	5(3)	125(78)	77(48)	13(8)
		TCC	1316	11(7)	124(77)	73(45)	11(7)
07/26/97	20-23	IR	592	0	164(102)	77(48)	15(9)
		TCC	558	35(22)	106(66)	72(45)	11.5(7)
07/27/97	12-20	IR	2414	0	230(143)	81(50)	14(9)
		TCC	2333	6(4)	110(68)	73(46)	11(7)
08/04/97	18-22	IR	974	0	145(90)	77(48)	14(9)
		TCC	1007	36(23)	116(72)	73(45)	12(7)

7.3.3 Length Analysis

Tables 7-4 and 7-5 are comparisons of lengths as determined by the two classification systems. Length accuracy is directly correlated with speed accuracy. Upon detection of a vehicle, each system first determines speed based on passage time of the front of the vehicle between two known points. Then, based on this speed, the detector monitors "presence." Vehicle classification for the TCC system using ILDs is based on length because length is the only parameter being monitored. Table 7-4 data reflect the speed bias of the infrared detector, indicating that lengths of trucks are consistently greater than measured with the TCC. The differences in sample means

Table 7-4. Length Comparison for Trucks in meters (feet)

Date	Hours	Sensor	Obs.	Min	Max.	Mean	Std.Dev.
07/25/97	10-14	IR	171	5(16)	19(64)	15(49)	5(17)
		TCC	142	6(20)	22(72)	14(47)	5(16)
07/26/97	20-23	IR	10	5(16)	19(64)	17(56)	5(16)
		TCC	13	7(23)	22(72)	14(48)	5(18)
07/27/97	12-20	IR	44	5(16)	19(64)	15(49)	5(17)
		TCC	49	6(22)	22(72)	13(43)	5(17)
08/04/97	18-22	IR	117	5(17)	19(63)	16(54)	5(15)
		TCC	109	6(20)	22(70)	15(49)	4.5(16)

Table 7-5. Length Comparison for Non-Trucks in meters (feet)

Date	Hours	Sensor	Obs.	Min	Max.	Mean	Std.Dev.
07/25/97	10-14	IR	1341	0	16(52)	5(16)	0.6(2)
		TCC	1316	1(3)	6(20)	4(13)	0.6(2)
07/26/97	20-23	IR	592	0	7.5(25)	5(17)	0.6(2)
		TCC	558	2(6)	5(17)	4(13)	0.5(2)
07/27/97	12-20	IR	2414	0	11(37)	5(17)	0.5(2)
		TCC	2333	1(4)	6(20)	4(13)	0.5(2)
08/04/97	18-22	IR	1030	0	12(40)	5(16)	0.6(2)
		TCC	1007	1(4)	6(20)	4(13)	0.6(2)

represented by each daily comparison is as much as 2.4 m (8 ft) greater with AS2 than with the TCC. The same bias is evident for non-trucks, but the discrepancies between the two detection systems are less with non-trucks. Even though the AS2 detector measures length, only height is currently used by the TTI software to detect trucks for purposes of extending a green signal.

7.3.4 Height Analysis

Table 7-6 is an analysis of height as measured by the AS2 detector. Height is the only classification parameter utilized by the infrared sensor; length could be used as a secondary classification variable, but it is not currently used. Because the minimum height to be classified as a truck in the TTI program is 2.3 m (7.5 ft), one would expect the minimum AS2 output heights to be 2.3 m (7.5 ft). That is, in fact, the case in the tabulated values. In the non-truck data, there were some minimum heights of zero feet, so these were considered as errors. These would cause the mean heights of non-trucks to be less than they really are.

Table 7-6. Height Analysis for Infrared Detector in meters (feet)

Date	Hours	Vehicle	Obs.	Min	Max.	Mean	Std.Dev.
07/25/97	10-14	Non-truck	1341	0	2(7)	1.6(5)	0.2(1)
		Truck	171	2.3(7.5)	4.3(14)	3.4(11)	0.6(2)
07/26/97	20-23	Non-truck	592	0	2.2(7)	1.6(5)	0.3(1)
		Truck	10	2.5(8)	4.3(14)	3.6(12)	0.7(2)
07/27/97	12-20	Non-truck	2414	0	2.2(7)	1.6(5)	0.25(1)
		Truck	44	2.3(8)	4.2(14)	3.4(11)	0.65(2)
08/04/97	18-22	Non-truck	1030	0	n/a	1.6(5)	0.25(1)
		Truck	117	2.3(8)	4.3(14)	3.6(12)	0.6(2)

7.3.5 Individually Matched Trucks

Following analysis of grouped data, TTI matched trucks over the same time periods and analyzed speeds on a paired vehicle basis. In other words, this analysis evaluated the same vehicle with the two systems and compared output speeds for that vehicle. The methodology used for the speed comparison for each truck subtracted the TCC speed from the AS2 speed for each truck based upon time stamps from each detection system. Results summarized in Table 7-7 indicate that infrared mean speeds were 11 km/h (7 mph) faster than TCC mean speeds on July 25, 1997 and 14 km/h (8.5 mph) faster on August 4, 1997. On July 25, the AS2 detector counted a total of 171 trucks, while the TCC system counted 142 trucks. Of these totals, there were 136 trucks that were matched by their time stamp. On August 4, there were 117 trucks detected by the AS2 and 109 by the TCC system. Of these totals, only 93 could be matched, again based on time stamps. The difference between individual and matched observations from the two samples indicates that some vehicles from each system were not classified as trucks.

Table 7-7. Speed Differences for Matched Trucks in km/h (mph)

Data Set	Count	Minimum	Maximum	Range	Mean	t-value
7/25/97	136	-11 (-7)	60 (37)	72 (44.5)	11(7)	26 (16)
8/4/97	93	-5 (-3)	87 (54)	92 (57)	14 (8.5)	19 (12)
8/4/97 edited	128	-5 (-3)	103 (64)	108 (67)	13 (8)	18 (11)

7.4 LANE TWO ANALYSIS AND COMPARISON

Table 7-8 lists the frequency of vehicles in each lane as measured by the TCC and are classified depending on the vehicle type. These data indicate a larger traffic volume in lane one, the outside lane. Lane two truck volumes consistently totaled about 20 percent of the lane one truck volumes. The other vehicle volumes for lane two equaled approximately 60 percent of the lane one volumes. The relationship between lane two counts and lane one counts indicates reasonable results, suggesting that the ILDs are operating properly.

Table 7-8. Lane One vs. Lane Two Counts for the TCC

Date	Time	Vehicle	Lane One Counts	Lane Two Counts
7/25/97	10-14	Non-Truck	1341	929
		Truck	171	30
7/26/97	20-23	Non-Truck	592	329
		Truck	10	2
7/27/97	12-20	Non-Truck	2414	1343
		Truck	44	18
8/04/97	18-22	Non-Truck	1030	611
		Truck	117	24

7.4.1 Speed Comparison

Lane one and lane two speeds measured by the TCC were also compared to evaluate operational effectiveness. Vehicles that drive in the inside lane of a divided highway (lane two) generally maintain higher speeds than vehicles traveling in the outside lane (lane one). However, these data were gathered at an approach to a signalized intersection where vehicles may not operate as they would in a free-flow highway situation. Lane one speeds are in Table 7-2, while lane two speeds are in Table 7-9. Non-truck mean speeds ranged from 72 km/h (45 mph) to 73 km/h (46 mph) for lane one, while lane two non-truck mean speed data ranged from 77 km/h (48 mph) to 79 km/h (49 mph). Truck mean speeds for lane one ranged from 67 km/h (42 mph) to 68 km/h (43 mph) and lane two covered an interval from 74 km/h (46 mph) to 81 km/h (50 mph). Vehicular mean speeds at the Sullivan City location varied little over the days in which data were collected for analysis. Lane two speeds averaged slightly higher than lane one speeds, as expected.

Table 7-9. Lane 2 TCC Speed Data in km/h (mph)

Date	Time	Vehicle	Obs.	Minimum	Maximum	Mean	Standard Deviation
7/25/97	10-14	Non-truck	929	6 (4)	125 (78)	80 (50)	12
7/25/97	10-14	Truck	30	61 (38)	105 (65)	74 (46)	12
7/26/97	20-23	Non-truck	329	15 (9)	117 (73)	77 (48)	12
7/26/97	20-23	Truck	2	78 (48)	93 (58)	85 (53)	11
7/27/97	12-20	Non-truck	1343	6 (4)	127 (79)	80 (50)	12
7/27/97	12-20	Truck	18	50 (31)	100 (62)	75 (47)	13
8/04/97	18-22	Non-truck	611	29 (18)	132 (82)	79 (49)	13
8/04/97	18-22	Truck	24	55 (34)	103 (64)	81 (50)	14

7.4.2 Length Comparison

The analysis compared vehicle lengths measured by the TCC comparing results from lanes one and two to check the consistency of measurements. Lane one data are in Table 7-3, while lane two length data are in Table 7-10. Lane one mean truck lengths fell between 13 m (43 ft) and 15 m (51 ft), while lane two mean truck lengths ranged from 12 m (39 ft) to 15 m (51 ft). All of the other vehicle mean lengths for both lanes one and two consistently measured 4 m (13 ft), which illustrates the precision of the TCC Loop Classification system.

7.5 ACOUSTIC DETECTOR ANALYSIS

As noted elsewhere, counts (or frequencies) provide a means for measuring reliability and consistency. Figures 7-1 through 7-4 show comparisons between the acoustic, infrared, and TCC systems for both trucks and non-trucks traveling eastbound on U.S. 83 in Sullivan City for August 18 and 19, 1997. Infrared and TCC loop data compare closely, but acoustic data indicate consistently smaller counts than either of the other two systems. Subsequent comparisons by vehicle type will be problematic because the classification scheme used by the SmartSonic is inconsistent with those of the other two systems. Table 7-11 indicates these four classifications. The acoustic counted only 80 percent of the vehicles counted by the infrared and TCC loop based systems throughout both days of data collection. The acoustic sensors maintained this same percentage for both lanes one and two, which is another check on its accuracy. It was suspected that lane two vehicles might get counted by the lane one sensor, but the counts indicate otherwise. This suggests that mounting angles and positioning were acceptable.

7.5.1 Vehicle Classification

Tables 7-12, 7-13, 7-14, and 7-15 display the classification counts generated by the acoustic system in its four classes, and compares these to total truck counts generated by the other two systems. For each hour represented, the acoustic detector shows an uncomfortably high number of vehicles that were unclassified. Lane one and lane two percentages unclassified on August 18, 1997 were 18 percent and 20 percent, respectively.

Table 7-10. Lane 2 TCC Length Data in m (ft)

Date	Time	Vehicle	Obs.	Minimum	Maximum	Mean	Standard Deviation
7/25/97	10-14	Non-truck	929	1 (3.3)	6 (20)	4 (13)	0.6
7/25/97	10-14	Truck	30	6.5 (21)	22 (72)	15 (49)	5.0
7/26/97	20-23	Non-truck	329	1 (3.3)	6 (20)	4 (13)	0.6
7/26/97	20-23	Truck	2	10 (33)	18 (59)	14 (46)	5.5
7/27/97	12-20	Non-truck	1343	1 (3.3)	6 (20)	4 (13)	0.5
7/27/97	12-20	Truck	18	6 (20)	21 (69)	12 (39)	5.0
8/04/97	18-22	Non-truck	611	1.5 (5)	6 (20)	4 (13)	0.6
8/04/97	18-22	Truck	24	6 (20)	20 66)	13 (43)	5.5

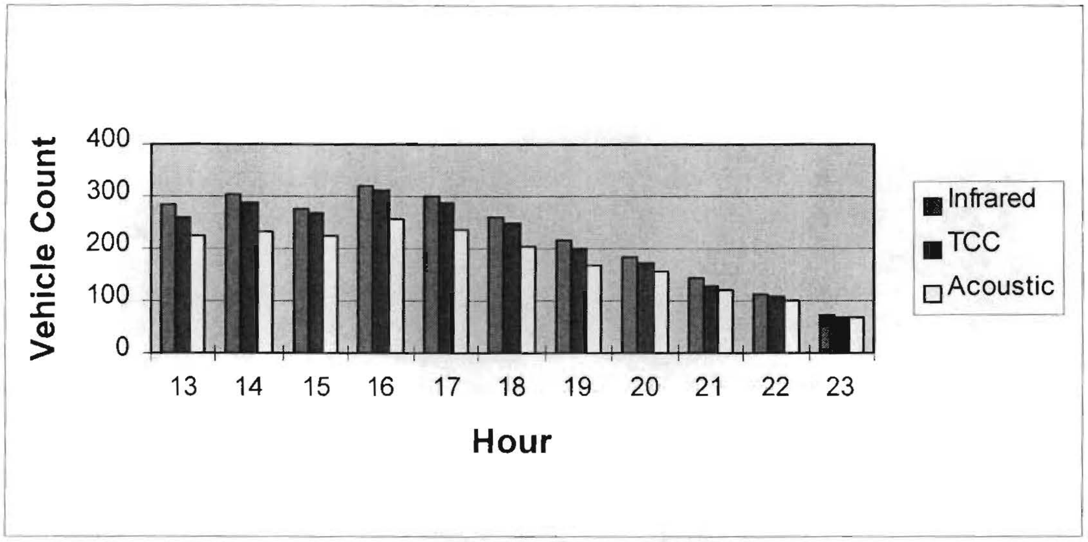


Figure 7-1. Vehicle Counts in Lane One (8/18/97)

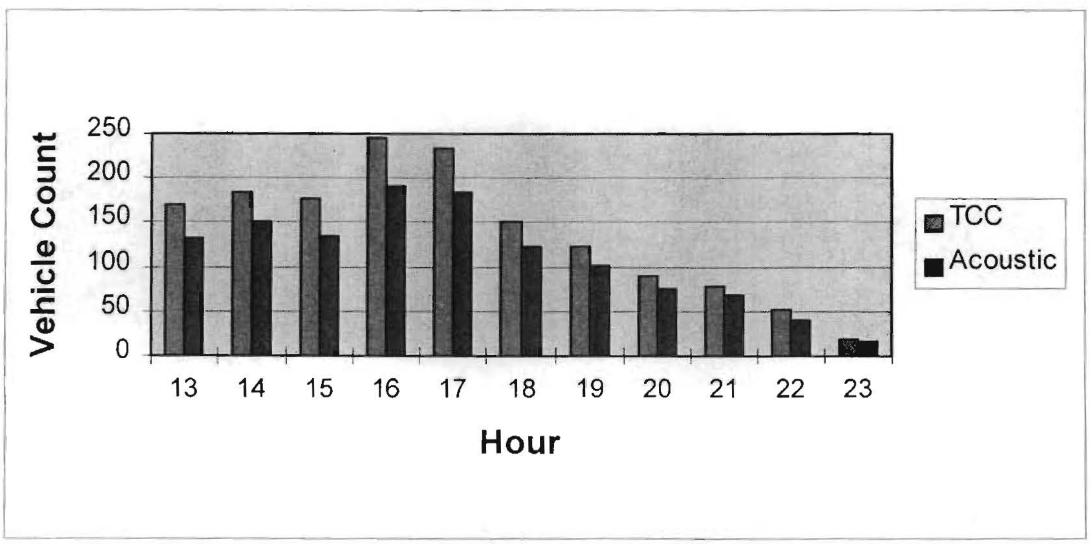


Figure 7-2. Vehicle Counts in Lane Two (8/18/97)

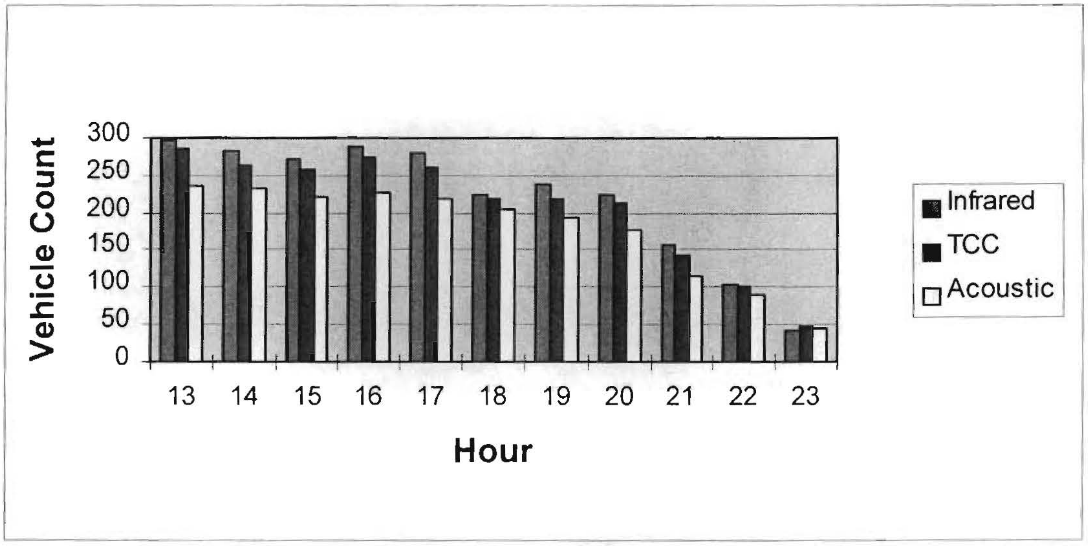


Figure 7-3. Vehicle Counts in Lane One (8/19/97)

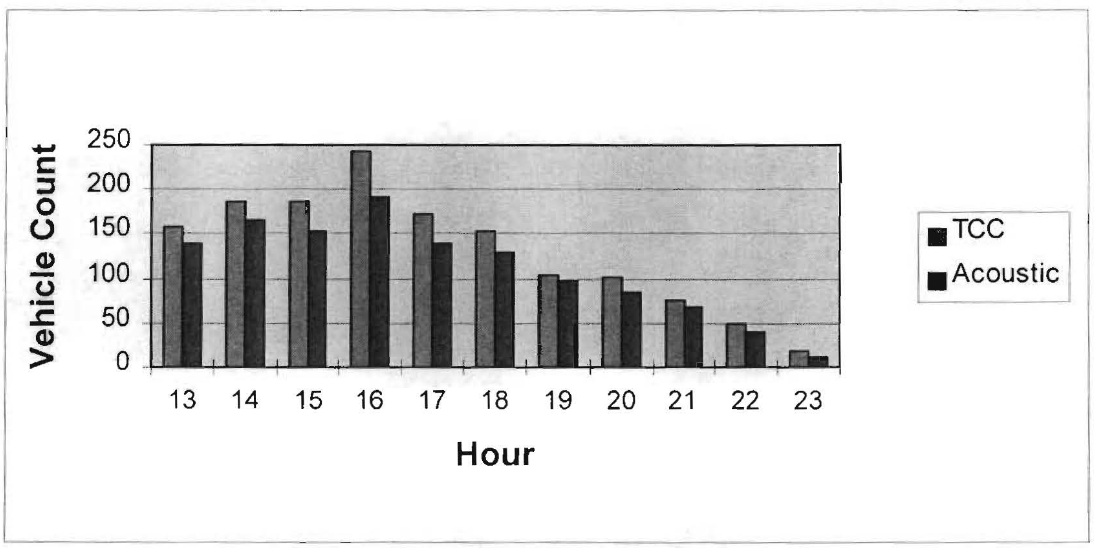


Figure 7-4. Vehicle Counts in Lane Two (8/19/97)

Table 7-11. SmartSonic Classification

Class	Vehicle Description
0	Unclassified
1	Cars
2	Small truck
3	Semi-Trailer

Table 7-12. Lane One Counts by Acoustic, Infrared, and TCC Systems (8/18/97)

Hour	SmartSonic Classification				Infrared Truck Counts	TCC Truck Counts
	0	1	2	3		
13	52	101	65	6	50	49
14	50	118	49	14	55	49
15	46	112	57	9	40	40
16	34	137	76	10	46	41
17	47	120	61	9	26	30
18	28	111	58	6	25	27
19	20	95	49	4	28	27
20	33	85	35	5	17	17
21	20	54	41	4	10	12
22	20	49	27	3	7	7
23	16	28	16	7	10	12
Sum	366	1010	534	77	314	311

Table 7-13. Lane Two Counts by Acoustic and TCC Systems (8/18/97)

Hour	SmartSonic Classification				TCC Truck Counts
	0	1	2	3	
13	26	67	37	3	7
14	36	66	48	2	8
15	28	65	38	4	8
16	35	91	62	2	15
17	39	82	59	5	10
18	26	49	43	5	7
19	20	50	30	1	6
20	17	40	18	0	4
21	15	28	23	2	3
22	5	17	18	1	1
23	2	9	6	0	2
Sum	249	564	382	25	71

Table 7-14. Lane One Counts by Acoustic, Infrared, and TCC Systems (8/19/97)

Hour	SmartSonic Classification				Infrared Truck Count	TCC Truck Count
	0	1	2	3		
13	55	106	63	12	33	33
14	43	111	64	14	41	34
15	43	121	46	11	40	30
16	40	107	68	12	42	35
17	33	118	64	4	27	23
18	34	114	49	8	21	22
19	34	98	53	8	28	27
20	37	87	46	7	21	19
21	14	64	33	3	8	7
22	11	47	27	4	10	12
23	3	28	14	1	4	5
Sum	347	1001	527	84	275	247

Table 7-15. Lane Two Counts by Acoustic and TCC Systems (8/19/97)

Hour	SmartSonic Classification				TCC Truck Counts
	0	1	2	3	
13	33	62	38	5	9
14	42	67	50	5	8
15	30	71	46	6	6
16	38	83	70	1	12
17	28	63	45	3	4
18	19	60	46	4	10
19	17	54	23	2	3
20	21	39	23	1	3
21	17	60	20	1	1
22	9	16	14	0	2
23	1	8	3	0	0
Sum	255	553	378	28	58

Data analysts were unable to find a correlation between vehicles classified as trucks by the acoustic system and other systems. Combining the acoustic's class 2 and class 3 (small trucks and semitrailer trucks) would sum to approximately three times the numbers generated by either the TCC system or the infrared system. Using only the acoustic's class 3 resulted in numbers that were approximately half the other two systems. The accuracy of the acoustic system might be improved by adjusting the acoustic sensor's sensitivity but there was insufficient time remaining to investigate the impact of the adjustment. Otherwise, initial results of this data comparison indicate that the acoustic detector is not sufficiently accurate for this application.

7.5.2 Speed Comparisons

The following analysis compares speeds measured by the SmartSonic system with those from the infrared and loop systems installed at the Sullivan City location. The acoustic system uses speed measurements for vehicle classification. However, the precise relationship between classification and speeds for the acoustic system is unclear. Tables 7-16, 7-17, 7-18, and 7-19 compare the speeds for all three systems. Vehicles labeled non-trucks represent class zero, one, and two for the acoustic system. Lane two truck volumes (class 3) were too low for a robust comparison. Acoustic speeds for non-trucks show an identical mean when compared to the infrared system, and the scatter, indicated by the standard deviation, was lower and matched the loop system's standard deviation. Acoustic mean speed typically measured 79 km/h (49 mph) in lane one and 92 km/h (57 mph) in lane two for non-trucks. The acoustic system's truck mean speed equaled 79 km/h (49 mph) in lane one and 112 km/h (70 mph) in lane two. The difference between speeds for the acoustic system and the TCC system differed more in lane two than lane one. There is a need to further investigate speed and count accuracy of the acoustic system, but based on these data it does not appear to be a reliable system for this application.

Table 7-16. Lane One Mean Speeds for All Systems (8/18/97)

Sensor	Vehicle	Counts	Minimum km/h (mph)	Maximum km/h (mph)	Mean km/h (mph)	Standard Deviatio n
Infrared	Non-trucks	2159	0	169 (105)	78 (49)	16 (10)
Acoustic	Non-trucks	1910	26 (16)	137 (85)	78 (49)	12 (7)
TCC	Non-trucks	2039	12 (7.5)	119 (74)	72 (45)	12 (7)
Infrared	Truck	314	37 (23)	169 (105)	80 (50)	17 (11)
Acoustic	Truck	77	45 (28)	121 (75)	79 (49)	18 (11)
TCC	Truck	311	31 (19)	116 (72)	66 (41)	12 (8)

Table 7-17. Lane Two Mean Speeds for All Systems (8/18/97)

Sensor	Vehicle	Counts	Minimum km/h (mph)	Maximum km/h (mph)	Mean km/h (mph)	Standard Deviatio n
Acoustic	Non-truck	1195	34 (21)	137 (85)	93 (58)	14 (8.5)
TCC	Non-truck	1452	8 (5)	116 (72)	78 (49)	12 (7.5)
Acoustic	Truck	25	64 (40)	141 (88)	112 (70)	30 (18.5)
TCC	Truck	71	32 (20)	116 (72)	72 (44.5)	15 (9)

Table 7-18. Lane One Mean Speeds for All Systems (8/19/97)

Sensor	Vehicle	Counts	Minimum km/h (mph)	Maximum km/h (mph)	Mean km/h (mph)	Standard Deviation
Infrared	Non-trucks	2134	0	281 (175)	79 (49)	15 (9.5)
Acoustic	Non-trucks	1875	22 (14)	143 (89)	79 (49)	11 (7)
TCC	Non-trucks	2036	11 (7)	117 (73)	73 (45)	11 (7)
Infrared	Truck	275	35 (22)	166 (103)	82 (51)	19 (12)
Acoustic	Truck	84	38 (24)	125 (78)	80 (50)	20 (13)
TCC	Truck	247	35 (22)	101 (63)	66 (41)	13 (8)

Table 7-19. Lane Two Mean Speeds for All Systems (8/19/97)

Sensor	Vehicle	Count	Minimum km/h (mph)	Maximum km/h (mph)	Mean km/h (mph)	Standard Deviation
Acoustic	Non-trucks	1186	37 (23)	143 (89)	92 (57)	13 (8)
TCC	Non-trucks	1391	8 (5)	116 (72)	79 (49)	12 (8)
Acoustic	Truck	28	51 (32)	145 (90)	110 (68)	30 (19)
TCC	Truck	58	47 (29)	96 (60)	74 (46)	13 (8)

Appendix Tables B-1 through B-3 list some of the important raw data gathered by the loop classification and infrared systems. Tables B-1 and B-2 account for the same data set observed on August 4, 1997, but Table B-1 shows the loop classification information, while Table B-2 represents the infrared data. Table B-1 provides the time each truck passed the sensors, but also shows the adjusted time (shown in seconds) which corresponds to the actual time the infrared system observed each truck. For instances where one sensor system picked up a truck and the other system did not, the vehicle type is listed as 'none.' Both tables include the vehicle speed and length, but Table B-2 also accounts for vehicle width and length because of the infrared system's ability to measure these dimensions. Table B-2 shows the speed difference between the measurements taken by each system. In Table B-1, the vehicles are classified by 'SU' (single-unit vehicle), 'Co' (combination unit), or 'PC' (passenger car). The vehicles recorded in Table B-2 can be identified by their observation number. Table B-3 includes practically the same information as Tables B-1 and B-2, but includes both the infrared and loop classification data for July 25, 1997.

7.6 PHASE HOLD OPERATION

TTI developed an interim method to test the accuracy of its software program for sending a green extension to the controller cabinet. This test monitors output from the program and prints a message when it would have sent the signal to extend the green if connected to a signal controller cabinet. Therefore, in the output, one could compare the vehicles detected as trucks and compare each detection with the message that indicates a green extension (GE) for that vehicle. This provides a precise indication of the accuracy of the TTI program. See chapter 4 for a description of initial tests in College Station.

In order to check phase hold accuracy for Sullivan City truck data, analysts individually matched and compared trucks and phase holds at the signalized intersection of U.S. 83 and F.M. 886. The phase hold requires conditions described in chapter 4 to be met before it sends the phase hold. If the vehicle is a truck and if the truck meets the speed criteria, then the software sends a signal to extend the green by the specified amount based on speed. At the site, the two systems used to trigger the phase hold were the infrared Autosense II sensor and the TCC loop system. The software reads the infrared message first, then the TCC classifier. If the infrared misses a truck, but the TCC detects a truck in the same lane, the software still sends a green extension. Table 7-20 shows that out of 128 observations identified as a truck by one of the two systems in the August 4, 1997 data set, there would have been 20 phase hold messages sent by the TCC system and 108 by the infrared system.

Table 7-20. Phase Hold Results

Data Set	Green Extensions	Sensor	Phase Holds
August 4, 1997	128	TCC	20
		AS2	108

7.7 IMPROVEMENTS DUE TO TRUCK DETECTION SYSTEM

One of the primary effects anticipated from the truck monitoring system is a reduction in delay to trucks and non-trucks on route being monitored. In this case, U.S. 83 traffic will get increased green time due to green extensions as trucks approach the intersection within the parameters described elsewhere in this report. These include trucks at speeds over 24 km/h (15 mph) approaching the signal on a green indication. The difference in delay to main street vehicles is the difference in "before" green time to "after" green time in which green time will be increased by the amount of the anticipated number of green extensions. In other words, these are vehicles that experience negligible delay with the green extension that would have otherwise been stopped because of the red signal.

The traffic signal in Sullivan City operates according to the signal timing parameters shown in Table 7-21. The phase sequence is as follows: 1 + 6, 2 + 6, 2 + 5, then 4, then 8. The signal controller is an Eagle EPAC 300 operating in a cabinet located on the southeast corner of the intersection.

7.7.1 Delay Improvements On the Main Street

The following analysis is based on a hypothetical scenario in which traffic signal parameters are applied to traffic count data at the Sullivan City intersection. As a rough approximation of the magnitude of possible delay savings expressed in dollars saved, the implications of delay savings on the main street and delay increase on the side street are then extrapolated to a yearly basis. A more accurate comparison can be done later once the number of green extensions per time period is documented. Over a 24-hour period, the truck and non-truck demand occurs according to the values shown in Table 7-22.

Table 7-21. Signal Timing Parameters at U.S. 83/F.M. 886

Phase	Dir.	Hwy.	Min. G.	Max. G.	Yellow	All Red
1	EB	U.S. 83	5	25	4	1
2	WB	U.S. 83	15	45	4	2
4	NB	F.M. 886	8	25	4	2
5	WB	U.S. 83	5	25	4	1
6	EB	U.S. 83	15	45	4	2
8	SB	F.M. 886	8	25	4	2
2	Ped		7	13		
6	Ped		7	13		
8	Ped		7	16		

Using only the 2 + 6 movement, and a maximum green of 45 seconds, one can determine some approximate time savings to trucks that approach near the end of the maximum green period. Based on observations at the site, trucks are dispersed such that every fourth 2 + 6 cycle might experience one or two trucks that extend the green. The green extension for typical truck speeds are 3.0 seconds for each truck, plus a partial extension of perhaps 2.0 seconds with the first truck that approaches just as the signal would have turned yellow. Using this scenario, it is

Table 7-22. Vehicular Demand at U.S. 83/F.M. 886

Beginning Hour	U.S. 83		F.M. 886
	No. Trucks	No. Non-Trucks	No. Non-Trucks
0	7	65	0
1	6	55	2
2	6	50	3
3	5	45	2
4	7	60	14
5	8	70	21
6	28	250	34
7	33	300	21
8	22	200	34
9	28	250	30
10	19	281	38
11	32	262	44
12	26	290	46
13	36	247	50
14	29	236	48
15	28	250	44
16	28	250	45
17	28	250	45
18	24	220	50
19	15	171	41
20	16	155	31
21	13	126	12
22	9	93	4
23	10	57	2

relatively easy to calculate the amount of delay savings that could accrue over a day or throughout a year.

Allowing a few additional trucks through the signal during each 2 + 6 phase means allowing non-trucks through also. Assuming that trucks and non-trucks are evenly dispersed for simplicity, based on arrival probabilities, there is anticipated to be just over a 3 percent chance that a truck arrival would occur at the end of a green phase that would stop without the truck detection system in operation. Trucks and non-trucks stopping have to wait at least the side street minimum green plus clearance interval and possibly as much as the maximum green plus clearance interval. Therefore, it is anticipated that time savings resulting from these trucks not stopping would result in an annual savings of $1,300. Likewise non-trucks would also experience reduced delay due to the green extension intended for trucks. The reduced delay to these non-trucks would amount to $2,600 in a year's time. Therefore, based on these delay reductions and minimal delay increases on the side street, the total savings associated with reduced delays to all vehicles over a year's time is anticipated to be $3,800 at this intersection. These estimates assume vehicle delays are improved only during the 12 peak hours of the day and for 50 weeks per year.

7.7.2 Delay Increase to the Side Street

The estimate of delay increase to side street traffic is based on video counts of traffic during a time period of three days. Traffic on the side street consisted only of non-trucks, and delay was again assessed at a value of $12 per hour of delay increase. In this case, the delay would only be for the amount of the green extension on the main street. Based on this and following similar logic as used above, the anticipated annual delay cost to the side street traffic would be under $100. This is considered negligible in this analysis.

7.7.3 Pavement Maintenance Improvements on the Main Street

According to district personnel, the costs of pavement damage at intersections due to trucks stopping averages $30,000 per intersection. Using similar improvement percentages as for delay, the reduction in pavement damage per year per intersection due to the truck detection system would be approximately $1,000.

7.7.4 Total System Savings

The total anticipated annual savings at this intersection would be the sum of savings from both reduced delay and reduced pavement damage. This total amounts to approximately $5,000. Therefore, depending on the total life-cycle cost of the truck detection system selected, the number of trucks on the main street, and the volume and type of traffic on the side street, there is anticipated to be an attractive benefit-cost relationship associated with the system. Also, this analysis ignored vehicle benefits, such as reduced brake and tire wear, that would also accrue.

8.0 IMPLEMENTATION

Results of this research are anticipated to have implications on future traffic signal design. If significant delay reductions accrue from signal changes, changes could result in both isolated and non-isolated intersection controller logic.

Findings of this research could result in changes to the method of signal detection and control that better accommodate the different deceleration characteristics of large trucks as compared to automobiles. Currently, traffic signal controllers do not distinguish between cars and large trucks. If signal timing needs to be adjusted based on a predominance of truck traffic, the signal technician might increase green extension or the yellow interval for the affected (usually high- speed) approaches. However, the vehicle monitoring system does not specifically identify trucks.

If there are cases where there are high truck flows resulting in significant improvement due to detecting trucks and altering the signal accordingly, there will be implications for adoption by the National Electrical Manufacturers Association (NEMA) in controller software. Also, possible expansion includes consideration of other approaches at the intersection and application to a series of closely spaced intersections where signal progression is possible.

Future versions or upgrades to the system developed by the TTI research team could use the Advanced Traffic Controller (ATC) 2070. The ATC 2070 controller is better suited for such applications than existing controllers for several reasons. For example, this research required staff to acquire from National Instruments, Inc. a digital I/O card and digital output modules capable of converting Direct Current signals from 3.3 VDC to 32 VDC to send a signal to the phase-hold connection on the controller's back panel. The ATC 2070 will come equipped with an I/O module capable of supporting 128 input and output signals.

In addition, the ATC 2070 has a flexible open architecture design that is based on the Versa Module Eurocard (VME). The 2070's Motorola processor supports multitasking, which allows multiple applications to run on the same processor. It also supports multiprocessing and can accommodate multiple CPUs in case one CPU is insufficient to run all desired applications. Communication with the current family of controllers is difficult because most have proprietary software and hardware, and the manufacturers rarely release details on how to communicate with their controllers. In some cases, the only means of communicating with a controller is by sending signals to affect various connections on the cabinet's back panel. The open architecture design makes communications between different applications running on the same or different 2070 CPUs possible and easier. The standard ATC 2070 backplane has four additional slots available for additional VME boards, making this controller very customizable and configurable by the user.

Future versions or upgrades of this software should implement the National Transportation Communication for ITS Protocol (NTCIP) standards for Advanced Traffic Sensor Messages for intersection applications. In the current project, TTI had to develop three different serial interface modules to communicate with the three sensors due to differences between serial communication protocols. If the manufacturers of traffic sensors would adopt the NTCIP standard for Traffic Sensor Messages, development and testing time would be reduced significantly. Also, once the serial interface is developed, it can be used with other sensors and for different applications.

These two advancements, the ATC 2070 and the NTCIP standard for Traffic Sensor Messages, will become more widespread in the very near future. As standards are adopted by traffic sensor manufacturers, the TTI system can become an off-the-shelf application that runs on any ATC 2070 if the intersection is equipped with the appropriate sensors.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 INTRODUCTION

The potential benefits from a truck sensing and priority system would be realized through trucks not having to stop (or having time to stop comfortably and safely) at isolated intersections. Avoiding hard truck stops would reduce pavement damage and rutting, lengthening pavement life, thereby, reducing maintenance costs and the delays caused by frequent pavement overlays. Based on ongoing research by the Texas Transportation Institute and sponsored by the Texas Department of Transportation *(67)*, several districts have experienced inductive loop failures near the intersection where heavy volumes of large trucks have caused pavement "shoving" and "rutting," which stress loop wires beyond their limits. Intersection safety would also be preserved, since truck drivers would not have to face the dilemma of either trying to stop abruptly during a yellow signal indication (which are more closely linked to the stopping capabilities of automobiles) or running a red light.

Another clear finding of the aforementioned study is the fact that several districts are already investigating non-intrusive detection technologies as replacements for inductive loops. The subject research to reduce stops to trucks also investigated several technologies to determine which ones would serve the needs specific to this research. A telephone survey sought to find the most appropriate detector with the following capabilities: reasonably priced, generated data via a serial port on a vehicle-specific basis, could accurately distinguish trucks from other vehicles, and vendor would provide access to its serial data protocols for interpretation purposes. From the survey, TTI selected two non-intrusive detectors -- a passive acoustic detector and an active infrared detector. It also selected a vehicle classifier system that could utilize either inductive loop detectors or piezoelectric detectors, or both, to serve as "ground truth" for data verification of test systems. Also, it could be used as the selected detector system if the non-intrusive technologies were found to be unsuitable for this application.

The objective of this research was to evaluate the feasibility of and demonstrate the application of a traffic signal system to reduce delays to commercial vehicles at isolated signalized intersections. This included finding information in the literature on such systems or their components, designing and testing hardware and software elements, purchasing and testing systems, installing equipment, performing field tests, and documenting study findings.

9.2 CONCLUSIONS

These conclusions are based on a literature search, field detector testing, evaluation of TTI's software to connect to the controller cabinet and extend the green phase, and an evaluation of vehicular delay resulting from implementation of the truck detection system. There were two phases of field testing, with the initial tests occurring in College Station at TTI's field test site facility and in its TransLink® lab on the Texas A&M University campus. The second series of tests occurred in the Pharr district in the small town of Sullivan City, located west of McAllen on U.S. 83. The primary conclusions are based on the data collected in the Pharr district.

In the context of the site in Sullivan City, there were problems that cannot be directly attributed to the detection systems, but which may be encountered elsewhere. One of the problems was in the power supply at the cabinet. For some reason, there were an inordinate number of power interruptions that forced the project team to reboot the computer and bring it back on-line. The system has the capability of being rebooted remotely via telephone line. Another problem experienced during the Sullivan City tests was with the telephone line. Long distance attempts to contact the site from College Station were often unsuccessful, especially in the afternoon hours possibly due to noisy phone lines. Finally, the use of the software PC Anywhere residing on the host computer at the site may have created some of the difficulties experienced by the project team.

9.2.1 Detector Acceptability

9.2.1.1 TCC System with Inductive Loops

The IRD vehicle classifier is a very robust and reasonably accurate system for collecting the truck classification and speed data necessary for this project. It represents a mature technology and its cost is approximately $2,500 (excluding detector costs). The primary errors experienced with it resulted from vehicles changing lanes in the vicinity of the sensors. There were also a few instances of vehicles passing on short headways that did not get classified accurately. The other problem experienced with this unit was its consistent and predictable ceasing of operation at or near midnight each day when the TTI program was running. In an autonomous mode, running by itself, this problem did not occur. TTI programmers successfully changed its internal clock several times so that it avoided midnight and it continued to function perfectly. Therefore, the problem is related to the internal data dump that it is programmed to perform at midnight.

The speed accuracy of the IRD system depends upon the type of sensors used for speeds and classifications. The recommended combination of sensors is two piezoelectric sensors and one inductive loop. With this combination of detectors, TTI researchers have experienced speed accuracy as high as plus-or-minus one percent. With only inductive loops, speed accuracy typically reduces to approximately plus-or-minus 5 percent. In research conducted at the Georgia Institute of Technology *(48)*, 13 sensor and classifier configurations from 10 commercially available equipment vendors were tested to determine their accuracy in classifying vehicles into 13 Federal Highway Administration (FHWA) classes. Classification accuracies ranged from 78.8 percent to 96.2 percent (combining class 2 and class 3 vehicles). In the TTI research, the TCC classifier misclassified 7.5 percent and missed 8.7 percent of vehicles in a sample of 160 vehicles.

9.2.1.2 Infrared Detector

One of the infrared detector's strengths is its ease of setup and its ability 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 the Autosense II requires mounting almost directly over the lane. This may require a special pole and mast arm as required in Sullivan City.

The detector's list price of $10,000 for one lane of coverage may be a constraint for some agencies, but the equipment 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 on the specific sensor 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 this application 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 the TCC system.

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.

9.2.1.3 Acoustic Detector

Cost of the acoustic detector system for two lanes was approximately $5,000, so its per-lane cost is an attractive feature. The TTI experience with this detector is the most 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 at Sullivan City, the SmartSonic detection system misclassified approximately 20 percent of vehicles. Its total vehicular count (all classes) for an 11-hour period on August 18, 1997 was 15 percent lower than the count by the TCC system. Every hour of this period was lower, by as much as 20 percent, compared to the TCC. Analysts could not verify its classification accuracy specifically relating to trucks because its classes did not correspond to those of the ground truth 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 TCC. For example, in the data set of approximately 2,000 non-trucks for August 18, 1997, its mean speed was 6 km/h (4 mph) faster than the TCC in lane one. Standard deviations were exactly the same for both systems at 12 km/h (7 mph). A much smaller data set for this date and lane one indicated a larger discrepancy for truck speeds -- the acoustic mean speed was 13 km/h (8 mph) faster than the TCC 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 TCC.

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.

9.2.2 TTI's Software to Extend the Green

The TTI research team developed a system including software and hardware components that detects large vehicles approaching a high-speed signalized intersection and extends the green time to allow these vehicles to pass through without conflict. The software programs consist of three modules: the serial interface module, the large vehicle identification module, and the green extension module. Refer to chapter 4 for a more detailed description of the software modules and hardware components of the system. The following two sections discuss the initial tests of the system in College Station and the field tests in Sullivan City.

9.2.2.1 Initial Laboratory and Field Tests in College Station

The software and hardware components of the system were tested in College Station at TTI's test site facility on S.H. 6 and in the TransLink® lab utilizing an Eagle EPAC 300 traffic controller and a fully functional cabinet. The field portions tested the serial interface and large vehicle identification modules using the AS2 and TCC detection systems. The Sonic sensor could not be tested due to delays in delivery and problems with the sensor. Once the lab tests of the green extension module were successful, the three modules were combined and tested in the field with both the AS2 and the TCC systems. In the absence of a cabinet for this portion of testing, staff tested the green extension module by observing the LEDs. These LEDs of the digital output modules used in the green extension module remained lit, indicating a signal was being sent for the duration of the green extension time. The green extension module extended the green every time a large vehicle was detected traveling at a speed that required extension. The duration of the green extension time, based on the speed of the vehicle, worked flawlessly during field observations.

9.2.2.2 Field Tests in Sullivan City

The research team continued field testing of the system after installation in Sullivan City. Staff encountered unprecedented problems in remotely connecting and controlling the system using the PCAnywhere software package. The PCAnywhere software package by SYMANTEC enables users to remotely control machines over telephone lines. Reasons for problems are still unknown but the quality of the telephone connection to Sullivan City is suspect. Staff ran the software program AS2TCC.exe that monitors both AS2 and the TCC together for several days, collecting data for various hours of weekdays and weekends. Results of field testing the system in Sullivan City, reflected the same trends as in College Station. The green extension module extended the green every time a large vehicle was detected traveling at speeds over 24 km/h (15 mph). The green extension time is user-definable, but is currently 3.0 seconds for trucks traveling at speeds above 72 km/h (45 mph) and 4.5 seconds for trucks traveling at speeds above 24 km/h (15 mph) and below 72 km/h (45 mph).

There were unique situations which demonstrated the accuracy of the software. Every time a large vehicle was detected by the AS2 sensor and the green time was extended, the module ignored the TCC detection of the same vehicle, as designed. In the Sullivan City installation, the AS2 sensor monitors the outer lane only while the TCC monitors both lanes. Each time the AS2 missed a truck on the outer lane that was detected by the TCC, the module extended the green time based on the TCC signal. The TCC also detected trucks on the inside lane, resulting in green time extension for every accurate detection. Therefore, based on tests both in College Station and in Sullivan City, the software developed by TTI performed as designed.

9.2.3 Impacts on Vehicle Delay and Pavement Maintenance

9.2.3.1 Main Street Delays

Allowing a few additional trucks through the signal during each U.S. 83 phase utilizing 2 + 6 movements means allowing non-trucks through also. Trucks and non-trucks stopping have to wait at least the side street minimum green plus clearance interval and possibly as much as the maximum green plus clearance interval. Therefore, it is anticipated that time savings resulting from these trucks not stopping would result in an annual savings of $1,300. Likewise non-trucks would also experience reduced delay due to the green extension intended for trucks. The reduced delay to these non-trucks would amount to an estimated $2,600 in a year's time. Therefore, the total savings associated with reduced delays to all vehicles over a year's time is anticipated to be $3,900 at this intersection.

9.2.3.2 Side Street Delays

The estimate of delay increase to side street traffic uses only non-trucks. In this case, the delay would only be for the modest amount of the green extension on the main street. Based on this, the anticipated annual delay cost to the side street traffic would be under $100. Therefore, from a practical standpoint, side street delay in this case is negligible.

9.2.3.3 Main Street Pavement Maintenance

According to district personnel, the costs of pavement damage at intersections due to trucks stopping averages $30,000 per intersection. Using similar improvement percentages as for delay, the reduction in pavement damage per year per intersection due to the truck detection system would be approximately $1,000.

Therefore, the total delay and maintenance costs reduced by the truck detection system at Sullivan City should be approximately $5,000 per year. For general application of the system in the future, there are several items to consider. The decision-maker must consider the total life-cycle cost of the truck detection system selected, the total number of trucks on the main street, and total traffic on the side street. For relatively high truck volumes and relatively low side street demand, an attractive benefit-cost relationship is anticipated. This analysis ignored vehicle benefits that would also accrue. The initial system cost of a viable system is in the range of $10,000 to $20,000.

9.3 RECOMMENDATIONS

9.3.1 Truck Detection System

Of the two non-intrusive detectors tested for this application, the infrared detector is favored for truck detection from the standpoint of speed and classification accuracy. Its requirement for an over-the-lane mounting and its cost are minor considerations not in its favor. Its long-term durability and maintenance costs must be evaluated to form a final conclusion on its effectiveness in comparison with the well-entrenched technology using pavement sensors. However, to perform a fair life-cycle comparison, costs of inductive loops must include installation delays to motorists, traffic control costs, and equipment costs over their true life cycle based on local experience. That comparison should be made at the appropriate time when sufficient maintenance costs have been documented for competing technologies as well as for inductive loops. Also, as other non-intrusive technologies such as video image detection systems improve in accuracy and costs decline, they too should be considered for such applications.

9.3.2 Impact on Vehicular Delays

Based on the truck and non-truck volumes in the U.S. 83 example, the truck detection system would not generate an attractive return on investment in the first year based solely on delay savings. However, other benefits such as reduced wear on vehicle components such as brakes and tires and reduced pavement wear would also accrue from fewer stops. Those benefits are beyond the scope of this research.

9.3.3 Future Research

There are several logical extensions to the current research that would improve truck movements either at isolated signalized intersections or within a system of multiple intersections where signal progression is a primary concern. The following discussion is not intended to apply to all roadways but only to those where heavy flows of trucks can be significantly disrupted by signal timing. The next logical step beyond the current project should continue to concentrate on single intersections because the control system must be successfully validated in this environment before being advanced into a more complicated scenario.

9.3.3.1 Isolated Intersections

The current truck detection algorithm only modifies signal timing if the signal is green on the truck approach. If the signal is red on that approach, nothing changes and the truck must stop or at least decelerate. The current module also only works with one set of approaches at the intersection, ignoring competing traffic on the side street. For the current truck detection algorithm to be complete, it needs to be enhanced to consider these other factors.

Now that classification and speed accuracies of the appropriate detectors are known, perhaps the next logical step is to continue working within the green extension module to add logic to determine whether side street demand is sufficient to warrant removing the green for trucks on the main street. Obviously, there is currently a fixed limit (user-definable) on the amount of green extension offered to trucks until the maximum is reached. However, additional research would address conditions on conflicting approaches which would override the maximum.

Another investigation would determine the feasibility of interrupting the red on the main street if a truck approaches. This would require moving truck detectors much further upstream on the main street to provide time to terminate the green phase on the side street and begin clearing queues on the main street before the truck arrived.

9.3.3.2 Multiple Intersections

Additional considerations at multiple intersections that might already function as part of a closed-loop system are size and acceleration characteristics of trucks. If trucks are required to stop at the first intersection in the system, the green progression band would consider their slower acceleration characteristics. If trucks do not stop, the system could possibly track their locations by their lengths and ensure progression for them unless preset (to be determined) criteria were not met.

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11.0 APPENDIX A
TRUCK SPEEDS ON U.S. 290

Table A-1. Truck Speeds on U.S. 290 at Mason Road

	DISTANCE FROM STOP LINE											
Class	600	500	400	300	200	100	0	L/U	Phase	Dir		
2s2		40	42	44	44	44	44		Green	Thru		
3s2		30	29	29	22	21	21		Green	Thru		
3s2			44	44	43	41	39	U	Green	Thru		
3s2	35	37	38	39	39	39	40	L	Green	Thru		
2s1	32		39	38	37	19			Green	Thru		
3s2	35		48	50	50	50	50		Green	Thru		
3s2	40	40	49	49	49	47	46		Green	Thru		
2s2	23	31	28	27	27	28	28		Green	Thru		
3s3	34	37	38	38	38	39	39	L	Green	Thru		
2s2	35	35	40	41	42	41	42	L	Green	Thru		
3s2	36	38	38	38	38	38	38	U	Green	Thru		
3s2			52	54	54	55	55		Green	Thru		
3s2	44	46	48		47	47	48		Green	Thru		
2s1	56		46	47	49	49	48		Green	Thru		
2s1	43	41	39	40	40	40	40		Green	Thru		
3s2	38		46	47	48	49	49		Green	Thru		
3s2			47	49	50	52	52		Green	Thru		
3s2		35	35	35	35	35	35		Green	Thru		
3s2	44	39	38	37	37		41		Green	Thru		
3s2	48	45	46	46	45	45	45		Green	Thru		
3s2			48	49	50	51	51		Green	Thru		
3s2		42	43	44	44	45	45		Green	Thru		
3s2	51	51	51	52	52	52	52		Green	Thru		
2s1	40	40	37	28					Green	Left		
3s2	40	40	44	44	44	44	44	U	Green	Thru		
3s2	45	45	53	55	56	56	56	L	Green	Thru		
3s2	47	47	54	54	55	57			Green	Thru		
3s2	57	57		48	48	48			Green	Thru		
3s2	40	44	46	47	47	48	49	U	Green	Thru		
3s2	39	40	50	49	50	50		L	Green	Thru		
3s2	34		44	44	45	46		U	Green	Thru		
3s2	38	38		41	41	41	43	U	Green	Thru		
3s2	48	51	52	53	54	54	54	U	Green	Thru		
3s2	31		42	42	42	42	41	U	Green	Thru		
3 2		49	53	51	55	55	55		Green	Thru		
3s2	40		42	44	45	45	45	U	Green	Thru		
3s2	27		37	38	38	38	38		Green	Thru		
3s2	32		44	46	46	46	46		Green	Thru		
3s2	44		51	50	50	51	51	U	Green	Thru		

3s2	46	46	44	45	46	47	47	L	Green	Thru		
3s2		37	35	33	34	36	38		Green	Thru		
Avg Spd	**40**	**42**	**44**	**44**	**44**	**44**	**44**					
3s2	49	48	45	41	37		0		Red	Thru		
3s2		42	42	42	30	25	0	U	Red	Thru		
3s2	52		55	55	31		0		Red	Thru		
2s2		46	43	40			0	L	Red	Thru		
3s2	34	35		24	19		0		Red	Thru		
3s2	27		32	35			0		Red	Thru		
3s3	35	34	33	29	22	18	0	L	Red	Thru		
3s2	27	32	33	34	34		0		Red	Thru		
3s2	35	35	35	34				U	Red	Thru		
3s2	31	30	29	24	22		0		Red	Thru		
2s1	39	37	35	22	18		0		Red			
3s2	38	39	35	32	28		0		Red	Thru		
3-2	49	47	47		25	25	0		Red	Left		
3-2	32	38	38	27	23		0		Red	Thru		
3s2	35	37	36	31	28	19	0		Red	Thru		
3s2	43	45	45	45	38		0		Red	Thru		
3s2	45	36	35	33	31		0		Red	Thru		
3s2	29	32	32	30	27	19	0	L	Red	Thru		
Avg Spd	**40**	**41**	**41**	**36**	**30**	**21**	**0**					
3s2	41	43	43	25			15		R-G	Thru		
3s2	32	35	35	33	28	23	21		R-G	Thru		
3s2		31	32	19	17	18	22		R-G	Thru		
3s2	42	33	35	37	37		41		R-G	Thru		
3s2	43	37	35	32	29	22	23	U	R-G	Thru		
3s2	37	30	28	25	25				R-G	Thru		
3s2	29	32	33	34	35	35	35		R-G	Thru		
3s2	43	47	48	49	50	50	51	U	R-G	Thru		
3s2		36	35	33	31	29	28		R-G	Thru		
Avg Spd	**39**	**36**	**36**	**32**	**32**	**30**	**30**					
3s2	53	51	48	25			0		G-R	Thru		
3s2	50	47	31			0	0		G-R	Thru		
3s2		43	41	37	23		0		G-R	Thru		
3s2	41	49	51	50	50	50	50		G-R	Thru	200	
3s2		63	63	60	61	61	61		G-R	Thru	300	
3s2		39	38	31			0		G-R	Thru	700	
3s2	37	36	35	21	20		0		G-R	Thru	800	
3s2	52	51	38	35	20		0		G-R	Thru	500	

3s2	52						0		G-R	Thru	500	
3s2	52	52	52	53	54	54	53		G-R	Thru	100	
3s2	50	50	50	51		18	0		G-R	Thru	400	
3s2	41	40	37	30			0		G-R	Thru	1000	
3s2	55	61	62	65	65	62	62		G-R	Thru	300	
3s2	45	45					0		G-R	Thru	500	
3s2	47	46	46	47	48	51	52		G-R	Thru	800	
3s2	50	50	35	30			0		G-R	Thru	1000	
3s2	43	41	38		22	15	0		G-R	Thru	700	
3s2	52	52		29		0			G-R	Thru	1000	
3s2	56	50		33			0		G-R	Thru	700	
3s2	56	55	55				0		G-R	Thru	400	
3s2	50	51	50	51	51	51	51		G-R	Thru	300	
3s2	49		53	54	54	55	55		G-R	Thru	200	
3s2	50		39	27	24		0		G-R	Thru	700	
3s2	43	40	38	34	25		0		G-R	Thru	1500	
3s2	45	42	40	32	22		0		G-R	Thru	800	
3s2	55		35	32	21		0		G-R	Thru	700	
3s2		53	54	54	32	17	10		G-R	Thru	300	Ran Red
3s2	51	55	35				0		G-R	Thru	700	
	1175	1162	1064	881	592	434	394					
	24	24	24	22	16	12	27					
	24	24	24	22	16	12	27					
Avg Spd	**49**	**48**	**44**	**40**	**37**	**36**	**15**					
Std Dev	5.15	6.79	9.15	12.7	16.8	24	24.5					
Lower CI	38.7	34.4	25.7	14.6	3.37	-12.1	-34					
Upper CI	59.3	61.6	62.3	65.4	70.6	84.1	63.9					

12.0 APPENDIX B

MATCHED DETECTOR DATA

Table B-1. Matched Loop Classification Data for 8/04/97

Hour	Min	Sec	Lane	Speed (mph)	Length (ft)	Truck	Vehicle	Sensor	Green	Adjusted Time
17	16	26	1	29.7	42.2	TRUCK	SU	TCC	GE	62257
17	17	54	1	40.3	28.8	TRUCK	SU	TCC	GNE	62345
17	18	35	1	43.4	20.7	TRUCK	SU	TCC	GE	62386
17	21	43	1	43.4	57.9	TRUCK	Co	TCC	GNE	62574
17	23	35	1	51.7	23.2	TRUCK	SU	TCC	GNE	62686
17	23	48	1	40.9	55.8	TRUCK	Co	TCC	GNE	62699
17	25	16	1	49.5	38.2	TRUCK	SU	TCC	GNE	62787
17	25	55	1	50.9	43.6	TRUCK	SU	TCC	GNE	62826
17	26	02	1	37.7	37.5	TRUCK	SU	TCC	GNE	62833
17	26	11	1	33.1	18.0	NONE	PC	TCC	GNE	
17	27	53	1	42.3	58.7	TRUCK	Co	TCC	GNE	62944
17	29	34	1	46.2	13.4	NONE	PC	TCC	GNE	
17	30	34	1	36.9	43.3	TRUCK	SU	TCC	GNE	63105
17	30	46	1	42.8	61.3	TRUCK	Co	TCC	GNE	63117
17	31	29	1	35.8	34.8	TRUCK	SU	TCC	GNE	63160
17	33	30	1	36.2	47.5	TRUCK	Co	TCC	GNE	63281
17	34	05	1	39.0	16.5	NONE	PC	TCC	GNE	
17	34	59	1	42.8	28.9	TRUCK	SU	TCC	GNE	63370
17	35	51	1	38.1	62.9	TRUCK	Co	TCC	GNE	63422
17	38	44	1	51.7	59.4	TRUCK	Co	TCC	GNE	63595
17	42	09	1	41.3	44.1	TRUCK	SU	TCC	GE	63800
17	46	04	1	48.8	54.3	TRUCK	Co	TCC	GNE	64035
17	49	30	1	40.8	56.6	TRUCK	Co	TCC	GNE	64241
17	54	51	1	37.3	17.7	NONE	PC	TCC	GNE	
17	55	20	1	38.1	17.4	NONE	PC	TCC	GNE	
17	58	35	1	36.2	40.3	TRUCK	SU	TCC	GNE	64786
17	59	10	1	45.6	50.0	TRUCK	Co	TCC	GNE	64821
17	59	50	1	39.5	14.3	NONE	PC	TCC	GNE	
18	02	41	1	54.1	55.2	TRUCK	Co	TCC	GNE	65032
18	02	45	1	48.1	67.6	TRUCK	Co	TCC	GNE	65036
18	04	12	1	35.5	64.9	TRUCK	Co	TCC	GNE	65123
18	05	00	1	33.7	17.4	NONE	PC	TCC	GNE	
18	10	03	1	36.6	30.9	TRUCK	SU	TCC	GE	65474
18	14	45	1	50.2	22.5	TRUCK	SU	TCC	GE	65756
18	15	29	1	35.1	49.8	TRUCK	Co	TCC	GNE	65800
18	15	45	1	28.2	42.1	TRUCK	SU	TCC	GNE	65816
18	21	26	1	35.8	53.9	TRUCK	Co	TCC	GNE	66157
18	25	26	1	45.0	17.9	NONE	PC	TCC	GNE	
18	26	37	1	36.6	14.0	NONE	PC	TCC	GNE	

Table B-1. Matched Loop Classification Data for 8/04/97 (continued)

Hour	Min	Sec	Lane	Speed (mph)	Length (ft)	Truck	Vehicle	Sensor	Green	Adjusted Time
18	27	54	1	57.7	61.1	TRUCK	Co	TCC	GNE	66545
18	32	09	1	52.6	14.0	NONE	PC	TCC	GNE	
18	34	42	1	41.3	32.1	TRUCK	SU	TCC	GE	66953
18	35	38	1	49.5	61.8	TRUCK	Co	TCC	GNE	67009
18	36	00	1	39.4	22.7	TRUCK	SU	TCC	GNE	67031
18	37	38	1	48.8	42.3	TRUCK	SU	TCC	GNE	67129
18	42	16	1	41.3	52.2	TRUCK	Co	TCC	GNE	67407
18	43	57	1	51.7	65.0	TRUCK	Co	TCC	GNE	67508
18	46	55	1	43.9	38.0	TRUCK	SU	TCC	GE	67686
18	47	23	1	47.6	47.8	TRUCK	Co	TCC	GNE	67714
18	47	29	1	55.9	14.7	NONE	PC	TCC	GNE	
18	51	31	1	39.0	58.4	TRUCK	Co	TCC	GNE	67962
18	52	47	1	43.9	59.9	TRUCK	Co	TCC	GNE	68038
18	52	55	1	25.6	55.7	TRUCK	Co	TCC	GE	68046
18	55	11	1	37.0	28.3	TRUCK	SU	TCC	GE	68182
18	58	03	1	48.8	66.6	TRUCK	Co	TCC	GNE	68354
18	58	56	1	30.0	45.5	TRUCK	Co	TCC	GNE	68407
18	59	18	1	42.4	30.0	TRUCK	SU	TCC	GE	68429
19	00	45	1	35.8	69.1	TRUCK	Co	TCC	GNE	68516
19	00	52	1	30.5	60.7	TRUCK	Co	TCC	GNE	68523
19	02	35	1	47.5	28.2	TRUCK	SU	TCC	GE	68626
19	04	27	1	46.2	15.1	NONE	PC	TCC	GNE	68738
19	08	12	1	28.3	16.5	NONE	PC	TCC	GNE	68963
19	10	34	1	44.0	13.8	NONE	PC	TCC	GNE	69105
19	13	01	1	55.9	19.3	NONE	PC	TCC	GNE	69252
19	24	32	1	33.8	53.8	TRUCK	Co	TCC	GNE	69943
19	25	58	1	50.3	59.5	TRUCK	Co	TCC		70029
19	27	28	1	46.3	62.4	TRUCK	Co	TCC		70119
19	29	54	1	42.4	50.5	TRUCK	Co	TCC		70265
19	37	23	1	48.2	60.1	TRUCK	Co	TCC	GNE	70714
19	38	39	1	56.8	64.6	TRUCK	Co	TCC	GNE	70790
19	39	51	1	52.6	66.0	TRUCK	Co	TCC	GNE	70862
19	39	55	1	45.7	68.8	TRUCK	Co	TCC	GNE	70866
19	49	35	1	48.9	39.9	TRUCK	SU	TCC	GNE	71446
19	49	45	1	42.9	66.2	TRUCK	Co	TCC	GNE	71456
19	54	08	1	53.3	64.2	TRUCK	Co	TCC	GNE	71719
19	57	33	1	43.5	69.9	TRUCK	Co	TCC	GNE	71924
19	59	40	1	44.6	13.1	NONE	PC	TCC	GNE	
20	03	41	1	35.9	61.0	TRUCK	Co	TCC	GNE	72292
20	09	19	1	47.6	55.0	TRUCK	Co	TCC	GNE	72630
20	10	19	1	51.0	58.6	TRUCK	Co	TCC	GNE	72690

Table B-1. Matched Loop Classification Data for 8/04/97 (continued)

Hour	Min	Sec	Lane	Speed (mph)	Length (ft)	Truck	Vehicle	Sensor	Green	Adjusted Time
20	10	41	1	33.8	44.1	TRUCK	SU	TCC	GNE	72712
20	10	44	1	34.5	49.9	TRUCK	Co	TCC	GNE	72715
20	11	24	1	38.7	49.8	TRUCK	Co	TCC	GNE	72755
20	11	27	1	35.5	51.0	TRUCK	Co	TCC	GNE	72758
20	12	00	1	48.2	22.2	TRUCK	SU	TCC	GE	72791
20	18	01	1	44.0	69.0	TRUCK	Co	TCC	GNE	73152
20	28	40	1	31.1	61.5	TRUCK	Co	TCC	GNE	73791
20	31	22	1	35.5	19.5	NONE	PC	TCC	GNE	
20	37	40	1	52.6	60.7	TRUCK	Co	TCC	GNE	74331
20	42	04	1	35.9	37.4	TRUCK	SU	TCC	GE	74595
20	42	56	1	42.9	44.7	TRUCK	SU	TCC	GNE	74647
20	56	17	1	43.0	67.6	TRUCK	Co	TCC	GNE	75448
20	57	15	1	43.0	45.4	TRUCK	Co	TCC	GNE	75506
20	57	51	1	31.4	66.9	TRUCK	Co	TCC	GNE	75542
21	00	44	1	37.5	19.6	NONE	PC	TCC	GNE	
21	04	41	1	51.8	20.7	TRUCK	SU	TCC	GNE	75952
21	10	33	1	36.7	35.5	TRUCK	SU	TCC	GE	76304
21	14	51	1	41.9	22.9	TRUCK	SU	TCC	GNE	76562
21	21	21	1	42.4	56.5	TRUCK	Co	TCC	GNE	76952
21	24	13	1	38.7	66.1	TRUCK	Co	TCC	GNE	77124
21	28	34	1	40.5	60.9	TRUCK	Co	TCC	GNE	77385
21	32	40	1	37.0	20.2	TRUCK	SU	TCC	GNE	77631
21	35	46	1	49.7	67.7	TRUCK	Co	TCC	GNE	77817
21	36	19	1	57.8	15.6	NONE	PC	TCC	GNE	
21	37	29	1	51.1	66.6	TRUCK	Co	TCC	GE	77920
21	37	37	1	53.5	54.1	TRUCK	Co	TCC	GNE	77928
21	42	47	1	33.2	53.8	TRUCK	Co	TCC	GNE	78238
21	43	34	1	43.5	18.4	NONE	PC	TCC	GNE	
21	49	44	1	51.1	65.7	TRUCK	Co	TCC	GNE	78655
21	54	02	1	48.3	24.1	TRUCK	SU	TCC	GNE	78913
22	11	32	1	40.0	66.8	TRUCK	Co	TCC	GNE	79963
22	22	38	1	42.0	25.3	TRUCK	SU	TCC	GE	80629
22	40	19	1	33.6	22.2	TRUCK	SU	TCC	GNE	81690
22	47	47	1	56.1	59.1	TRUCK	Co	TCC	GNE	82138
22	48	50	1	35.2	47.8	TRUCK	Co	TCC	GNE	82201
22	48	57	1	26.4	57.3	TRUCK	Co	TCC	GNE	82208
22	53	53	1	50.4	52.7	TRUCK	Co	TCC	GNE	82504
22	58	5	1	34.9	58.5	TRUCK	Co	TCC	GNE	82756
22	58	10	1	30.6	67.1	TRUCK	Co	TCC	GNE	82761
23	01	58	1	42.4	48.5	TRUCK	Co	TCC	GE	82989
23	09	40	1	46.5	26.1	TRUCK	SU	TCC	GE	83451

Table B-1. Matched Loop Classification Data for 8/04/97 (continued)

Hour	Min	Sec	Lane	Speed (mph)	Length (ft)	Truck	Vehicle	Sensor	Green	Adjusted Time
23	09	45	1	44.7	28.3	TRUCK	SU	TCC	GE	83456
23	14	56	1	44.1	21.7	TRUCK	SU	TCC	GE	83767
23	24	13	1	53.5	53.3	TRUCK	Co	TCC	GNE	84324
23	29	48	1	44.1	51.0	TRUCK	Co	TCC	GNE	84659
23	36	57	1	40.0	19.0	NONE	PC	TCC	GNE	
23	45	35	1	42.5	61.2	TRUCK	Co	TCC	GNE	85606
23	49	38	1	44.6	49.7	TRUCK	Co	TCC	GNE	85849
23	49	47	1	44.1	46.2	TRUCK	Co	TCC	GNE	85858
23	50	10	1	37.5	21.6	TRUCK	SU	TCC	GNE	85881

Table B-2. Matched Infrared Classification Data for 8/04/97

Actual Time	Hour	Min	Sec	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Sensor	Speed Difference
62257	17	17	37	55	6	90	6.3	21.3	19	46	NONE		16.3
62345	17	19	5	62	7	80	12.8	38.8	28	46	TRUCK	as2	5.7
62395	17	19	55	68	7	90	8.0	38.8	20	56	TRUCK	as2	12.6
62574	17	22	54	77	9	80	13.8	63.8	28	51	TRUCK	as2	7.6
62686	17	24	46	87	7	80	12.5	31.5	24	55	TRUCK	as2	3.3
62699	17	24	59	89	9	80	13.8	63.8	28	48	TRUCK	as2	7.1
62787	17	26	27	102	9	90	10.5	56.5	23	61	TRUCK	as2	11.5
62826	17	27	6	105	9	90	9.5	60.5	26	56	TRUCK	as2	5.1
62833	17	27	13	106	9	70	7.5	51.8	28	43	TRUCK	as2	5.3
62842	17	27	22	108	7	90	9.5	31.0	25	36	TRUCK	as2	
62945	17	29	5	118	9	90	14.0	63.8	26	56	TRUCK	as2	13.7
63045	17	30	45	125	7	90	11.3	19.0	27	49	TRUCK	as2	
63105	17	31	45	131	9	90	10.0	57.5	26	41	TRUCK	as2	4.1
63117	17	31	57	132	9	80	13.8	63.8	28	49	TRUCK	as2	6.2
63160	17	32	40	138	9	90	10.0	59.5	22	49	TRUCK	as2	13.2
63281	17	34	41	146	9	90	8.0	63.8	21	43	TRUCK	as2	6.8
63316	17	35	16	150	7	90	10.8	21.0	24	40	TRUCK	as2	
63370	17	36	10	156	7	80	12.8	37.3	28	48	TRUCK	as2	5.2
63422	17	37	02	158	9	80	13.8	63.8	28	45	TRUCK	as2	6.9
63595	17	39	55	166	9	90	13.3	63.8	24	66	TRUCK	as2	14.3
64036	17	47	16	204	9	80	14.0	63.8	28	56	TRUCK	as2	7.2
64065	17	47	45	206	7	90	8.0	34.5	15	37	TRUCK	as2	
64241	17	50	41	217	9	90	14.0	63.8	25	51	TRUCK	as2	10.2
64562	17	56	02	240	7	90	10.5	22.0	24	40	TRUCK	as2	
64592	17	56	32	241	7	80	10.0	29.0	28	48	TRUCK	as2	
64786	17	59	46	0	9	90	9.8	52.3	21	38	TRUCK	as2	1.8
64821	18	00	21	3	9	90	12.0	63.3	25	48	TRUCK	as2	2.4
64861	18	01	01	9	5	90	8.3	18.5	22	42	TRUCK	as2	
65032	18	03	52	20	9	80	14.0	63.8	28	61	TRUCK	as2	6.9
65036	18	03	56	21	9	90	13.8	63.8	27	52	TRUCK	as2	3.9
65123	18	05	23	26	10	90	11.5	63.8	26	39	TRUCK	as2	3.5
65170	18	06	10	29	7	90	9.3	26.3	26	35	TRUCK	as2	
	18	11	14	55	5	90	6.0	39.8	22	42	NONE		5.4
	18	15	56	78	5	90	6.0	15.5	20	51	NONE		0.8
65800	18	16	40	81	9	90	10.0	63.8	27	43	TRUCK	as2	7.9
65817	18	16	57	82	9	90	10.0	60.3	20	34	TRUCK	as2	5.8
66157	18	22	37	102	9	90	11.8	63.8	25	40	TRUCK	as2	4.2
66344	18	25	44	117	7	80	11.0	27.3	23	61	TRUCK	as2	
66398	18	26	38	123	7	80	9.0	29.3	28	52	TRUCK	as2	
66468	18	27	48	131	5	80	7.5	24.5	25	51	TRUCK	as2	
66545	18	29	05	138	9	90	13.5	63.8	27	80	TRUCK	as2	22.3

Table B-2. Matched Infrared Classification Data for 8/04/97 (continued)

Actual Time	Hour	Min	Sec	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Sensor	Speed Difference
66800	18	33	20	156	9	30	13.3	63.8	3	117	TRUCK	as2	
	18	35	53	168	6	90	6.0	18.5	23	42	NONE		0.7
67009	18	36	49	175	9	80	14.0	63.8	28	56	TRUCK	as2	6.5
67031	18	37	11	176	7	90	13.0	43.0	27	46	TRUCK	as2	6.6
67129	18	38	49	187	9	90	10.3	53.5	27	56	TRUCK	as2	7.2
67407	18	43	27	206	9	90	9.3	63.8	24	46	TRUCK	as2	4.7
67508	18	45	08	212	9	80	14.0	63.8	28	61	TRUCK	as2	9.3
	18	48	06	220	6	90	6.3	18.8	22	46	NONE		2.1
67714	18	48	34	223	9	90	11.0	63.8	25	56	TRUCK	as2	8.4
67720	18	48	40	224	5	90	8.0	17.0	22	56	TRUCK	as2	
67962	18	52	42	236	9	90	10.5	63.8	24	49	TRUCK	as2	10.0
68038	18	53	58	241	9	90	13.8	63.8	27	52	TRUCK	as2	8.1
68047	18	54	7	242	9	80	12.8	63.8	28	28	TRUCK	as2	2.4
68354	18	59	14	10	9	80	14.0	63.8	28	56	TRUCK	as2	7.2
68408	19	00	08	13	9	90	12.0	62.5	22	35	TRUCK	as2	5.0
	19	00	29	16	6	90	6.3	18.3	22	46	NONE		3.6
68517	19	01	57	21	9	80	14.0	63.8	28	43	TRUCK	as2	7.2
68524	19	02	04	22	9	90	13.5	63.8	23	35	TRUCK	as2	4.5
	19	03	46	28	5	90	6.8	16.3	22	52	NONE		4.5
68737	19	05	37	35	7	80	13.3	27.5	28	56	TRUCK	as2	
68963	19	09	23	48	7	80	9.5	27.0	28	35	TRUCK	as2	
69104	19	11	44	56	5	90	7.8	18.3	25	52	TRUCK	as2	
69251	19	14	11	66	7	90	10.8	27.0	27	66	TRUCK	as2	
69944	19	25	44	95	9	90	13.0	63.0	23	37	TRUCK	as2	3.2
70030	19	27	10	101	9	80	13.8	63.8	28	66	TRUCK	as2	15.7
70119	19	28	39	105	9	90	13.5	63.8	24	56	TRUCK	as2	9.7
70265	19	31	05	111	9	90	13.8	63.8	27	56	TRUCK	as2	13.6
70715	19	38	35	131	9	80	14.0	63.8	28	56	TRUCK	as2	7.8
70790	19	39	50	136	9	80	14.0	63.8	28	66	TRUCK	as2	9.2
70862	19	41	02	142	9	90	14.0	63.8	26	66	TRUCK	as2	13.4
70867	19	41	07	143	9	90	13.8	63.8	27	52	TRUCK	as2	6.3
71446	19	50	46	180	9	90	11.3	49.3	24	56	TRUCK	as2	7.1
71456	19	50	56	182	9	90	13.8	63.8	27	49	TRUCK	as2	6.1
71719	19	55	19	194	9	80	14.0	63.8	28	61	TRUCK	as2	7.7
71925	19	58	45	205	9	90	13.3	63.8	26	52	TRUCK	as2	8.5
72052	20	00	52	216	7	80	12.0	30.0	19	49	TRUCK	as2	
72293	20	04	53	228	9	80	13.8	63.8	28	41	TRUCK	as2	5.1
72630	20	10	30	241	9	80	14.0	63.8	28	61	TRUCK	as2	13.4
72691	20	11	31	244	9	80	13.0	63.8	28	56	TRUCK	as2	5.0
72712	20	11	52	245	10	70	12.5	50.5	28	39	TRUCK	as2	5.2
72715	20	11	55	247	9	90	10.8	63.8	25	46	TRUCK	as2	11.5

Table B-2. Matched Infrared Classification Data for 8/04/97 (continued)

Actual Time	Hour	Min	Sec	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Sensor	Speed Difference
72756	20	12	36	250	9	80	10.0	63.8	28	56	TRUCK	as2	17.3
72759	20	12	39	251	9	90	9.8	63.8	27	66	TRUCK	as2	30.5
	20	13	11	253	5	90	6	17.3	23	52	NONE		3.8
73152	20	19	12	15	9	80	13.8	63.8	28	52	TRUCK	as2	8.0
73791	20	29	51	48	9	90	13.3	63.8	24	37	TRUCK	as2	5.9
73953	20	32	33	56	7	80	13.3	40.5	28	46	TRUCK	as2	
74332	20	38	52	75	9	90	13.8	63.8	26	66	TRUCK	as2	13.4
	20	43	15	93	6	90	6.0	17.3	23	52	NONE		5.1
74647	20	44	7	98	9	90	9.3	63.8	16	49	TRUCK	as2	6.1
75449	20	57	29	135	9	80	13.8	63.8	28	52	TRUCK	as2	9.0
75506	20	58	26	138	9	90	10.0	60.0	21	46	TRUCK	as2	3.0
75543	20	59	3	143	9	80	14.0	63.8	28	35	TRUCK	as2	3.6
75715	21	01	55	150	7	90	12.0	37.0	22	43	TRUCK	as2	
75951	21	05	51	161	7	90	13.0	35.0	26	61	TRUCK	as2	9.2
	21	11	44	181	5	80	5.8	19.5	23	43	NONE		6.3
76562	21	16	02	192	7	90	11.8	30.5	19	39	TRUCK	as2	- 2.9
76953	21	22	33	207	9	80	12.8	63.8	28	56	TRUCK	as2	13.6
77125	21	25	25	214	9	80	14.0	63.8	28	46	TRUCK	as2	7.3
77386	21	29	46	225	9	80	14.0	63.8	28	49	TRUCK	as2	8.5
77630	21	33	50	237	7	80	11.3	34.5	28	41	TRUCK	as2	4.0
77817	21	36	57	241	9	80	13.8	63.8	28	61	TRUCK	as2	11.3
77850	21	37	30	245	7	70	13.0	43.0	28	90	TRUCK	as2	
77920	21	38	40	248	9	80	14.0	63.8	28	56	TRUCK	as2	4.9
77928	21	38	48	249	9	90	13.5	63.8	24	66	TRUCK	as2	12.5
78240	21	43	60	2	9	80	12.5	63.8	23	39	TRUCK	as2	5.8
78284	21	44	44	3	7	90	13.0	33.3	27	49	TRUCK	as2	
78655	21	50	55	16	9	90	14.0	63.8	25	61	TRUCK	as2	9.9
78913	21	55	13	24	9	80	8.3	63.8	25	102	TRUCK	as2	53.7
79964	22	12	44	55	9	90	13.8	63.8	23	43	TRUCK	as2	3.0
	22	23	49	79	3	90	4.0	15.8	16	43	NONE		1.0
81690	22	41	30	104	7	80	13.0	40.0	28	41	TRUCK	as2	7.4
82138	22	48	58	121	9	80	14.0	63.8	28	72	TRUCK	as2	15.9
82202	22	50	02	124	9	80	10.0	63.8	28	46	TRUCK	as2	10.8
82209	22	50	09	125	9	90	11.0	63.8	25	32	TRUCK	as2	5.6
82505	22	55	05	132	9	90	10.0	63.8	27	61	TRUCK	as2	10.6
82757	22	59	17	140	9	80	14.0	63.8	28	43	TRUCK	as2	8.1
82762	22	59	22	141	9	80	14.0	63.8	28	35	TRUCK	as2	4.4
82989	23	03	09	148	9	90	11.0	63.8	25	49	TRUCK	as2	6.6
	23	10	51	159	3	70	5.3	14.8	20	49	NONE		2.5
	23	10	56	161	5	90	6.3	17.3	25	46	NONE		1.3
83768	23	16	08	169	7	80	11.3	37.8	28	52	TRUCK	as2	7.9

Table B-2. Matched Infrared Classification Data for 8/04/97 (continued)

Actual Time	Hour	Min	Sec	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Sensor	Speed Difference
84324	23	25	24	181	9	80	12.0	63.8	28	61	TRUCK	as2	7.5
84659	23	30	59	189	9	90	13.0	63.8	23	49	TRUCK	as2	4.9
85088	23	38	08	194	7	80	12.8	34.5	28	46	TRUCK	as2	
85606	23	46	46	198	9	80	9.8	63.8	28	49	TRUCK	as2	6.5
85849	23	50	49	205	9	80	12.0	62.5	28	49	TRUCK	as2	4.4
85858	23	50	58	206	9	80	11.0	59.5	28	49	TRUCK	as2	4.9
85881	23	51	21	207	7	80	13.0	42.0	28	46	TRUCK	as2	8.5

Table B-3. Matched Loop Classification and Infrared Data for 7/25/97

Infrared Data												Loop Classification Data					
Hour	Min	Sec	Time (sec)	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Time (sec)	Lane	Speed (mph)	Length (ft)	Class	Speed Difference
10	00	13	36013	26	5	80	7.5	16.3	18	48	TRUCK						
10	01	57	36117	38	9	80	13.8	63.8	28	55	TRUCK	36193	1	49	60.7	Co	6.0
10	07	59	36479	67	9	90	14.0	63.8	24	51	TRUCK	36555	1	48	58.7	Co	3.3
10	08	43	36523	72	5	80	7.5	24.8	22	55	TRUCK						
10	10	49	36649	85	7	90	8.3	35.0	23	42	TRUCK	36725	1	38	23.0	SU	3.8
10	12	39	36759	98	7	80	11.8	20.8	16	60	TRUCK	36902	1	38	33.4	SU	21.3
10	12	40	36760	99	9	80	13.5	61.8	22	60	TRUCK	37141	1	41	51.5	Co	18.6
10	17	45	37065	128	9	90	10.0	63.8	24	45	TRUCK						
10	20	51	37251	151	9	80	13.8	63.8	28	36	TRUCK	37327	1	29	61.7	Co	6.6
10	21	13	37273	153	9	80	9.8	63.8	28	65	TRUCK	37349	1	49	57.5	Co	16.0
10	21	50	37310	160	7	80	11.8	43.0	28	65	TRUCK	37387	1	52	23.6	SU	13.0
10	26	29	37589	185	7	90	9.0	26.3	22	60	TRUCK	38072	1	49	29.5	SU	11.0
10	33	21	38001	212	9	80	13.8	63.8	28	55	TRUCK	38077	1	46	62.0	Co	8.6
10	35	11	38111	222	5	80	7.5	18.5	23	51	TRUCK						
10	37	35	38255	237	7	90	8.8	32.8	25	45	TRUCK	38332	1	43	24.0	SU	2.0
10	43	19	38599	7	9	90	10.0	63.8	22	60	TRUCK	38676	1	52	49.6	Co	8.0
10	46	9	38769	21	5	90	7.8	18.5	27	51	TRUCK						
10	46	41	38801	22	9	80	12.5	57.3	23	48	TRUCK	38877	1	42	44.0	SU	5.6
10	47	37	38857	27	9	90	11.0	63.8	21	56	TRUCK	38932	1	48	50.5	Co	7.7
												39108	1	36	33.4	SU	
10	53	37	39217	58	9	80	10.0	63.8	29	38	TRUCK	39293	1	32	54.6	Co	5.9
10	54	14	39254	65	9	80	10.5	63.8	28	55	TRUCK	39331	1	44	54.2	Co	11.0
10	54	28	39268	67	7	90	9.0	36.8	24	51	TRUCK	39345	1	51	34.9	SU	0.5
10	56	55	39415	80	9	90	9.5	63.8	22	36	TRUCK	39491	1	32	47.9	Co	3.9
10	59	15	39555	85	9	80	14.0	63.8	28	55	TRUCK	39632	1	41	60.4	Co	13.7
11	01	35	39695	98	9	90	9.3	53.0	24	34	TRUCK	39771	1	30	39.3	SU	3.6
11	01	40	39700	99	7	90	9.0	23.3	25	40	TRUCK	39777	1	40	21.1	SU	0

Table B-3. Matched Loop Classification and Infrared Data for 7/25/97 (continued)

Infrared Data												Loop Classification Data					
Hour	Min	Sec	Time (sec)	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Time (sec)	Lane	Speed (mph)	Length (ft)	Class	Speed Difference
11	03	11	39791	108	9	80	13.8	63.8	28	60	TRUCK	39868	1	47	56.5	Co	13.0
11	03	35	39815	109	9	80	12.0	63.8	28	45	TRUCK	39891	1	35	49.6	Co	9.9
11	04	02	39842	111	9	80	13.8	63.8	28	45	TRUCK	39917	1	39	63.2	Co	6.0
11	04	36	39876	113	9	80	9.5	63.8	28	40	TRUCK	39952	1	33	56.1	Co	6.6
11	06	34	39994	127	9	80	13.8	63.8	28	65	TRUCK	40070	1	57	68.9	Co	7.9
11	09	04	40144	136	7	90	13.0	40.5	27	48	TRUCK	40221	1	42	25.1	SU	6.1
11	10	20	40220	144	7	90	9.8	44.5	26	55	TRUCK	40296	1	44	30.5	SU	11.0
11	11	11	40271	147	9	80	9.5	56.0	28	42	TRUCK	40348	1	40	46.0	Co	1.6
11	12	01	40321	151	7	80	9.8	22.0	28	48	TRUCK	40398	1	47	20.1	PC	1.0
11	16	05	40565	164	7	90	11.0	31.5	26	51	TRUCK	40641	1	48	23.6	SU	3.4
11	18	38	40718	181	9	80	13.8	63.8	28	60	TRUCK	40794	1	47	69.1	Co	13.0
11	21	14	40874	195	7	90	10.8	20.8	20	48	TRUCK						
11	22	47	40967	204	7	80	9.8	32.8	28	37	TRUCK	41043	1	35	27.3	SU	2.3
11	23	54	41034	211	9	80	10.8	63.8	28	56	TRUCK	41110	1	44	50.9	Co	12.0
11	26	15	41175	226	9	80	13.8	63.8	28	60	TRUCK	41251	1	52	66.5	Co	8.1
11	27	38	41258	237	7	90	10.5	30.5	22	43	TRUCK	41334	1	43	25.0	SU	0.1
11	29	51	41391	246	7	80	10.8	21.5	28	55	TRUCK						
11	30	23	41423	248	7	90	8.0	25.8	26	40	TRUCK						
11	33	27	41607	6	9	80	13.8	63.8	28	55	TRUCK	41683	1	46	63.5	Co	9.2
11	33	41	41621	8	9	90	13.8	63.8	27	38	TRUCK	41697	1	35	64.3	SU	3.3
11	39	20	41960	32	7	80	13.3	35.5	28	48	TRUCK	42037	1	44	21.6	SU	4.0
11	42	11	42131	48	9	80	9.8	63.8	28	45	TRUCK	42207	1	40	52.4	Co	5.1
11	42	36	42156	51	9	80	9.8	63.8	28	51	TRUCK	42232	1	45	48.1	Co	5.9
												42296	1	35	36.0	SU	
11	45	27	42327	63	9	80	13.8	63.8	28	55	TRUCK	42403	1	45	66.4	Co	9.8
11	45	34	42334	64	9	80	13.5	63.8	28	41	TRUCK	42410	1	32	64.6	Co	9.1
11	45	38	42338	65	9	80	9.3	63.8	28	32	TRUCK	42413	1	28	56.0	Co	4.5

Table B-3. Matched Loop Classification and Infrared Data for 7/25/97 (continued)

Infrared Data												Loop Classification Data					
Hour	Min	Sec	Time (sec)	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Time (sec)	Lane	Speed (mph)	Length (ft)	Class	Speed Difference
11	49	33	42573	80	7	80	11.8	30.5	28	33	TRUCK	42649	1	30	24.0	SU	2.8
11	49	52	42592	81	9	90	10.0	63.8	26	39	TRUCK	42668	1	34	48.5	Co	5.0
11	49	57	42597	82	9	90	10.8	63.8	26	41	TRUCK	42672	1	33	48.8	Co	8.3
11	55	56	42956	113	5	90	8.0	19.8	26	71	TRUCK						
11	56	56	43016	119	7	90	10.3	29.3	27	42	TRUCK	43093	1	39	23.9	SU	3.4
11	58	22	43102	129	9	80	14.0	63.8	28	65	TRUCK	43178	1	50	56.9	Co	14.6
12	01	10	43270	147	7	80	11.8	32.0	28	65	TRUCK						
12	02	15	43335	152	7	80	9.0	21.5	28	34	TRUCK	43284	1	41	31.1	SU	-7.3
12	03	10	43390	155	9	90	9.5	63.8	25	40	TRUCK	43466	1	32	48.0	Co	7.9
12	04	19	43459	162	9	90	11.8	62.0	25	55	TRUCK	43535	1	47	46.1	Co	8.0
12	08	22	43702	179	9	80	13.8	63.8	28	65	TRUCK	43778	1	52	63.1	Co	13.1
12	09	48	43788	187	9	90	11.8	47.8	23	48	TRUCK	43864	1	45	38.6	SU	3.5
												43878	1	45	27.9	SU	
12	11	44	43904	199	7	90	8.5	30.3	24	38	TRUCK	43980	1	37	21.6	SU	0.7
12	13	22	44002	210	7	90	10.3	21.3	26	51	TRUCK						
12	14	47	44087	213	7	90	10.8	20.8	22	45	TRUCK						
12	19	03	44343	240	9	90	14.0	63.8	26	55	TRUCK	44420	1	50	55.4	Co	5.3
12	24	46	44686	17	7	90	10.8	27.3	20	40	TRUCK						
12	25	46	44746	23	9	90	13.8	63.8	25	40	TRUCK	44821	1	38	57.7	Co	2.3
12	28	02	44882	35	9	90	9.5	63.8	26	71	TRUCK	44958	1	51	51.6	Co	19.8
12	32	03	45123	57	9	80	13.8	63.8	28	51	TRUCK	45199	1	46	53.5	Co	5.3
12	34	60	45300	73	5	90	8.0	22.5	15	45	TRUCK	45693	1	43	46.3	Co	1.6
12	38	60	45540	97	8	90	9.8	21.8	23	42	TRUCK	45710	1	37	23.4	SU	4.7
12	41	18	45678	111	9	90	13.8	63.8	27	51	TRUCK	45754	1	45	62.5	Co	5.9
12	42	03	45723	115	9	90	13.5	63.8	24	48	TRUCK	45799	1	37	53.5	Co	11.1
12	42	10	45730	116	9	90	10.0	63.8	25	38	TRUCK	45806	1	34	64.0	Co	4.3
12	42	14	45734	117	7	90	12.8	40.8	26	38	TRUCK	45810	1	32	21.8	SU	5.6

Table B-3. Matched Loop Classification and Infrared Data for 7/25/97 (continued)

Infrared Data												Loop Classification Data					
Hour	Min	Sec	Time (sec)	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Time (sec)	Lane	Speed (mph)	Length (ft)	Class	Speed Difference
12	43	28	45808	126	7	70	12.5	29.5	28	45	TRUCK						
12	46	21	45981	143	9	80	11.0	63.8	28	78	TRUCK	46058	1	62	62.7	Co	15.9
12	46	37	45997	144	7	80	13.5	37.8	28	48	TRUCK	46073	1	45	30.0	SU	2.9
12	47	14	46034	148	9	90	9.0	55.5	26	45	TRUCK	46110	1	38	38.7	SU	6.9
12	49	19	46159	157	7	80	12.8	42.5	28	45	TRUCK	46236	1	35	24.1	SU	9.6
12	52	38	46358	170	9	90	13.8	63.8	27	55	TRUCK	46434	1	45	66.2	Co	9.9
12	54	16	46456	180	9	80	13.8	63.8	28	48	TRUCK	46531	1	35	64.2	Co	12.6
12	54	43	46483	181	9	90	11.8	63.8	25	38	TRUCK	46559	1	32	52.3	Co	5.9
12	56	19	46579	193	9	90	10.3	63.8	26	51	TRUCK	46655	1	39	49.2	Co	11.6
12	58	43	46723	208	9	80	13.5	63.8	28	60	TRUCK	46799	1	51	62.5	Co	8.9
13	01	60	46920	224	7	90	10.0	29.5	24	51	TRUCK	46996	1	45	23.0	SU	6.5
13	03	28	47008	232	9	80	12.8	49.5	28	55	TRUCK	47084	1	50	40.0	SU	5.3
13	05	35	47135	247	7	80	12.5	37.3	24	60	TRUCK	47211	1	54	26.8	SU	6.5
13	06	16	47176	250	7	90	10.0	35.8	26	55	TRUCK	47253	1	49	21.6	SU	6.1
13	06	34	47194	252	9	90	13.5	63.8	27	65	TRUCK	47269	1	52	60.6	Co	13
13	07	03	47223	254	7	90	8.0	27.5	27	45	TRUCK						
13	07	50	47270	1	7	70	12.5	45.8	28	55	TRUCK	47346	1	49	35.2	SU	6.1
13	08	51	47331	4	9	80	13.8	63.8	28	71	TRUCK	47407	1	61	71.2	Co	10.0
13	08	55	47335	5	9	80	13.8	63.8	28	65	TRUCK	47411	1	53	62.1	Co	12.3
13	09	43	47383	8	9	80	9.0	63.8	28	38	TRUCK	47459	1	32	50.4	Co	6.2
												47744	1	43	31.5	SU	
13	14	41	47681	28	7	90	8.8	34.5	25	42	TRUCK	47758	1	39	25.9	SU	3.0
13	15	45	47745	34	9	90	13.0	63.8	23	51	TRUCK	47821	1	45	65.0	Co	6.5
13	15	59	47759	35	7	90	13.5	42.3	27	48	TRUCK	47835	1	45	34.9	SU	2.9
13	16	42	47802	39	9	90	13.8	63.8	26	48	TRUCK	47878	1	42	63.2	Co	6.2

Table B-3. Matched Loop Classification and Infrared Data for 7/25/97 (continued)

Infrared Data												Loop Classification Data						
Hour	Min	Sec	Time (sec)	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Time (sec)	Lane	Speed (mph)	Length (ft)	Class	Speed Difference
13	19	29	47969	47	9	80	13.8	63.8	28	60	TRUCK	48046	1	51	60.1	Co	8.9
13	19	54	47994	54	9	80	13.8	63.8	28	51	TRUCK	48070	1	43	61.7	Co	7.6
13	20	00	48000	56	9	90	14.0	63.8	26	38	TRUCK	48076	1	35	64.6	Co	2.9
13	20	07	48007	57	7	80	12.8	35.3	28	40	TRUCK						
13	24	29	48269	71	9	90	9.8	63.8	25	42	TRUCK	48345	1	37	53.2	Co	4.7
13	25	08	48308	78	5	80	7.5	18.3	25	45	TRUCK						
13	26	21	48381	83	9	80	13.8	63.8	28	51	TRUCK	48457	1	46	62.2	Co	5.3
13	27	36	48456	86	9	90	9.8	63.8	26	51	TRUCK	48532	1	43	51.6	Co	8.2
13	28	29	48509	90	7	80	13.0	40.0	28	42	TRUCK	48586	1	38	21.8	SU	4.3
13	29	04	48544	94	9	80	14.0	63.8	28	55	TRUCK	48620	1	45	60.5	Co	9.9
13	29	08	48548	95	9	80	13.8	63.8	28	48	TRUCK	48624	1	43	60.0	Co	5.2
13	29	14	48554	96	7	90	9.0	24.0	17	55	TRUCK						
13	30	37	48637	105	9	90	9.3	63.8	22	48	TRUCK	48713	1	43	51.1	Co	5.2
13	30	51	48651	107	7	90	8.0	32.0	27	38	TRUCK	48727	1	35	20.5	PC	3.3
13	33	23	48803	120	9	90	9.8	63.8	19	34	TRUCK	48878	1	31	51.4	Co	2.8
13	35	34	48934	125	7	90	8.8	27.0	24	48	TRUCK						
13	40	17	49217	149	9	90	9.3	63.8	27	60	TRUCK	49293	1	52	52.4	Co	8.2
13	43	39	49419	170	7	80	10.3	25.8	28	60	TRUCK						
13	44	53	49493	174	9	90	10.0	63.8	24	51	TRUCK	49569	1	40	44.8	SU	10.6
13	46	17	49577	183	9	80	10.5	52.3	28	65	TRUCK	49653	1	56	39.1	SU	8.9
												49779	1	48	28.2	SU	
13	48	33	49713	202	7	90	9.0	37.0	27	36	TRUCK	49789	1	33	27.8	SU	3.0
13	49	13	49753	206	9	80	14.0	63.8	28	55	TRUCK	49830	1	53	62.3	Co	2.3
13	52	59	49979	226	9	90	9.3	63.8	26	40	TRUCK	50054	1	36	64.2	Co	3.8
13	53	09	49989	227	5	80	8.3	18.5	19	45	TRUCK						
13	54	38	50078	237	9	90	13.5	63.8	23	51	TRUCK	50154	1	45	63.3	Co	5.9
13	54	44	50084	238	9	90	10.3	63.8	27	60	TRUCK	50160	1	42	47.6	Co	18.2

Table B-3. Matched Loop Classification and Infrared Data for 7/25/97 (continued)

Infrared Data												Loop Classification Data					
Hour	Min	Sec	Time (sec)	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Time (sec)	Lane	Speed (mph)	Length (ft)	Class	Speed Difference
13	56	45	50205	243	9	80	13.3	63.8	28	65	TRUCK	50282	1	54	64.5	Co	11.5
14	01	05	50465	8	9	90	14.0	63.8	26	30	TRUCK	50540	1	27	63.3	Co	3.4
14	01	36	50496	12	7	90	12.0	35.0	25	48	TRUCK	50572	1	42	26.1	SU	5.7
14	01	59	50519	14	7	80	12.3	29.3	23	45	TRUCK	50596	1	41	21.8	SU	3.7
14	02	26	50546	17	7	90	12.8	36.5	27	55	TRUCK	50622	1	51	28.3	SU	3.9
14	02	57	50577	18	9	80	11.3	63.8	28	48	TRUCK	50653	1	40	54.3	Co	7.7
14	03	30	50610	20	9	80	13.5	63.8	28	36	TRUCK	50685	1	32	67.4	Co	3.9
14	06	47	50807	34	9	80	13.5	63.8	28	55	TRUCK	50883	1	47	61.6	Co	8.1
14	09	47	50987	46	7	80	12.5	33.0	22	31	TRUCK	51063	1	29	24.8	SU	1.9
14	15	51	51351	78	9	80	14.0	63.8	28	60	TRUCK	51427	1	48	61.4	Co	11.8
14	16	60	51420	81	7	90	9.8	44.3	26	51	TRUCK	51496	1	46	35.5	SU	5.3
14	17	33	51453	84	9	90	9.0	63.3	23	36	TRUCK	51529	1	33	49.3	Co	3.0
14	24	14	51854	117	7	80	10.8	23.3	28	60	TRUCK						
14	24	36	51876	121	10	80	13.0	63.8	28	78	TRUCK	51952	1	41	34.2	SU	37.2
14	24	38	51878	123	9	90	7.8	63.0	23	48	TRUCK						
14	24	51	51891	125	9	80	13.3	63.8	28	45	TRUCK	51967	1	37	58.8	Co	8.5
14	26	01	51961	128	7	90	11.0	22.8	24	48	TRUCK						
14	26	09	51969	129	9	80	13.5	63.8	28	60	TRUCK	52045	1	53	58.1	Co	7.3
14	26	33	51993	130	7	80	8.3	31.8	28	55	TRUCK	52069	1	44	20.8	PC	11.1
14	27	14	52034	135	9	90	13.5	63.8	27	40	TRUCK	52110	1	34	63.6	Co	5.3
14	27	23	52043	136	9	80	13.5	63.8	28	48	TRUCK	52119	1	43	55.2	Co	5.1
14	28	09	52089	139	9	90	13.8	63.8	25	51	TRUCK	52165	1	40	59.8	Co	10.7
14	28	29	52109	140	5	90	8.0	24.3	21	42	TRUCK						
14	28	56	52136	143	7	80	10.8	42.8	28	48	TRUCK	52213	1	39	23.3	SU	9.5
14	31	08	52268	156	7	90	11.5	22.5	27	48	TRUCK						
14	34	01	52441	172	9	90	13.5	63.8	24	55	TRUCK	52517	1	50	60.2	Co	4.7
14	39	06	52746	198	9	80	13.8	63.8	28	60	TRUCK	52822	1	48	61.5	Co	11.8

Table B-3. Matched Loop Classification and Infrared Data for 7/25/97 (continued)

Infrared Data												Loop Classification Data					
Hour	Min	Sec	Time (sec)	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Time (sec)	Lane	Speed (mph)	Length (ft)	Class	Speed Difference
14	43	36	53016	217	7	90	9.8	25.5	26	48	TRUCK	52923	1	44	71.3	Co	4.1
												53073	1	45	31.9	SU	
												53075	1	43	27.7	SU	
14	45	01	53101	222	7	80	9.3	33.0	28	38	TRUCK	53177	1	37	25.8	SU	1.1
14	45	46	53146	226	9	80	13.8	63.8	28	65	TRUCK	53222	1	57	59.9	Co	8.0
14	46	39	53199	231	7	90	10.0	23.8	22	48	TRUCK						
14	49	17	53357	240	9	90	13.8	63.8	26	42	TRUCK	53433	1	39	69.3	Co	3.4
14	49	55	53395	242	7	90	8.3	25.0	21	38	TRUCK						
14	50	19	53419	244	5	80	8.3	20.0	28	51	TRUCK						
14	50	24	53424	245	5	80	7.5	16.5	24	45	TRUCK						
14	53	01	53581	255	9	80	9.3	60.0	26	48	TRUCK						
14	53	04	53584	0	9	90	10.8	63.8	22	38	TRUCK	53660	1	33	50.9	Co	5.3
14	53	18	53598	3	9	90	10.8	63.8	26	48	TRUCK	53673	1	41	51.3	Co	6.7
14	53	22	53602	4	9	90	10.0	63.8	27	49	TRUCK	53678	1	41	51.1	Co	7.7
14	58	57	53937	29	9	80	12.5	52.0	23	60	TRUCK	54013	1	51	36.7	SU	9.0
14	59	21	53961	30	9	90	13.5	63.8	23	48	TRUCK	54037	1	40	60.4	Co	8.2
14	59	33	53973	33	7	80	8.5	33.8	28	33	TRUCK	54050	1	32	22.3	SU	1.2
14	59	54	53994	34	9	80	13.8	63.8	28	43	TRUCK	54069	1	36	63.2	Co	6.9
15	00	03	54003	35	9	90	13.0	63.8	26	26	TRUCK	54078	1	23	54.1	Co	2.9
15	00	17	54017	36	9	90	9.8	57.8	20	42	TRUCK	54092	1	40	47.5	Co	2.2
15	01	25	54085	43	9	90	9.3	63.8	27	40	TRUCK	54161	1	36	51.7	Co	3.9
15	02	33	54153	49	9	80	13.8	63.8	28	48	TRUCK	54229	1	42	52.5	Co	5.7
15	03	20	54200	55	9	80	11.3	63.8	29	55	TRUCK	54277	1	43	50.5	Co	12.2
15	06	06	54366	63	9	80	9.3	63.8	28	40	TRUCK	54442	1	37	55.4	Co	3.1
15	06	35	54395	66	9	80	9.8	63.8	28	45	TRUCK	54471	1	37	55.2	Co	7.8
15	08	25	54505	74	5	50	8.0	9.0	0	65	TRUCK						
15	09	33	54573	78	7	80	12.8	38.0	28	55	TRUCK	54649	1	50	29.4	SU	5.4

Table B-3. Matched Loop Classification and Infrared Data for 7/25/97 (continued)

Infrared Data												Loop Classification Data					
Hour	Min	Sec	Time (sec)	Obs	Class	Conf	Height (ft)	Length (ft)	Width (ft)	Speed (mph)	Type	Time (sec)	Lane	Speed (mph)	Length (ft)	Class	Speed Difference
15	10	48	54648	84	9	80	9.5	63.8	28	55	TRUCK	54724	1	48	66.2	Co	7.5
15	11	34	54694	87	9	90	9.5	63.8	25	51	TRUCK	54770	1	43	50.7	Co	8.2
												54773	1	39	33.9	SU	-39
15	13	22	54802	95	9	90	10.5	63.8	22	45	TRUCK	54877	1	38	52.6	Co	6.9
15	15	05	54905	105	9	90	13.5	63.8	27	65	TRUCK	54981	1	56	60.6	Co	9.0

13.0 APPENDIX C

OPERATIONS MANUAL

OPERATIONS MANUAL

1.1 Power Requirements

1.1.1 Autosense II Infrared Detector

The AutoSense II system requires 120 VAC 60 Hz available to the location of sensor installation.

1.2.1 SmartSonic Acoustic Detector

The SmartSonic requires 120 VAC 60 Hz at the controller. The Controller transfers 24 VAC to the location of sensor installation.

1.3.1 TCC Loop Classification System

The TCC Loop Classification requires 120VAC at the classifier for battery recharging purposes.

2.1 Operational Software

2.1.1 Autosense II Infrared Detector

The AutoSense II uses the AS2test.exe program to test the initial setup and configuration of the sensor without using serial protocol transmission.

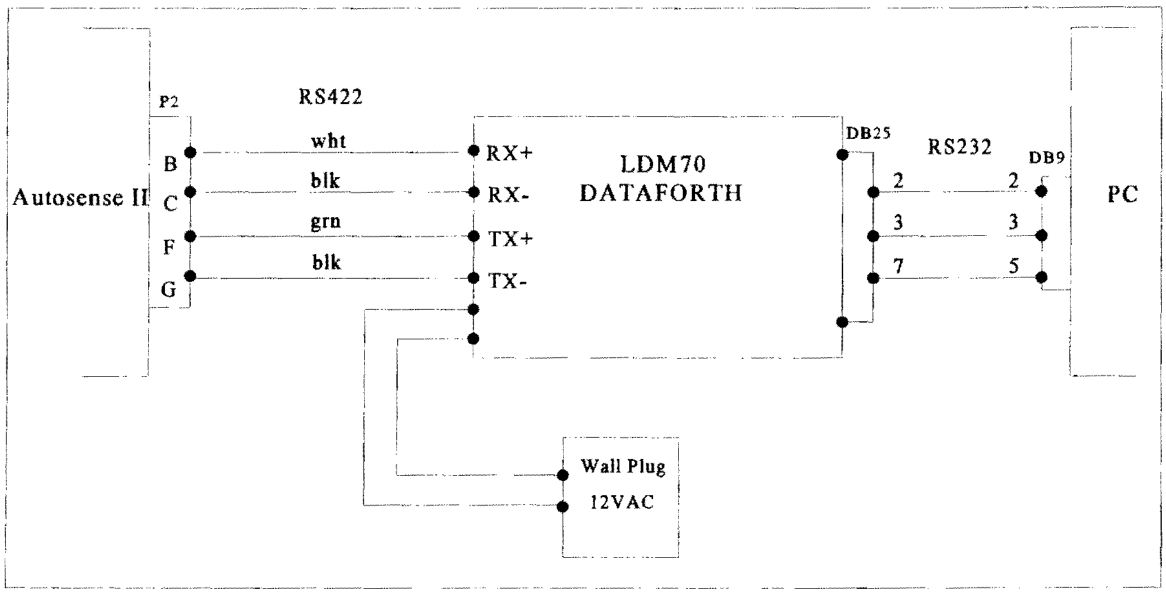
2.1.2 SmartSonic Acoustic Detector

The SmartSonic System utilizes a terminal provided by Microsoft. These packages are standard with all Windows-based computers. Instructions are given in the SmartSonic manual for specific command utilized within the TSS-1 Controller.

2.1.3 TCC Loop Classification System

The TCC Loop Classification system software is Trafman.exe. This software is a DOS based package.

3.1 Hardware Configuration



4.1. Operational Checklist

AutoSense II Serial Interface Setup Checklist

The software AS2TEST.EXE:

- Verify that the latest version AS2TEST.EXE is being used (VER 1.01.26 as of 6-23-97).

- Select the correct serial port from the configure software section (COM1 or COM2).

- Select the baud rate to be 57.6.

- Execute the "Save PC configuration" to save this setup.

LDM70:

- When properly connected the TD and RD LED indicators will most often be **OFF**, coming **ON** momentarily during the passage of a burst of data.

- See attached LDM70 installation instructions for more details.

- DTE / DCE Switch setting: When using a standard straight-through Com cable - set switch to **DCE**

LED Indicators	Normal Operation	RX+ or RX- Open circuit	DTE - DCE switch setting wrong	TX+/- and RX+/- swapped
RLSD	ON	OFF	ON	OFF
RD	OFF	ON	OFF	ON
DTR	ON *	ON *	ON *	ON *
TD	OFF	OFF	ON	OFF

* OFF when using a serial cable without DTR.

5.1 Software Operations Manual

The TTI research team developed software programs to monitor the sensors installed in Sullivan City. The software programs developed include: the **AS2.exe**, the **TCC.exe**, and the **AS2TCC.exe** programs. The first two programs, the AS2.exe and the TCC.exe, monitor one sensor each. The third program, the AS2TCC.exe, monitors both the AS2 sensor and the TCC classifier together. The programs are located in the "C:\Sullivan\Apps" subdirectory on the industrial PC. The following paragraphs provide instructions on how to operate the three software programs, how to shut down and reboot the industrial PC remotely over the telephone, and describe the system configuration parameters that can calibrate and affect the system performance. Chapter 4 includes a detailed discussion of the program modules, the data received from each sensor, the classification criteria for each sensor, and a description of the green time extension mechanism.

5.1.1 The AS2.exe Software Program

The AS2.exe program monitors the AS2 sensor alone. To start the program, double click on the AutoSenseII shortcut icon on the industrial PC desktop. The program can also be started by selecting the AutoSenseII option from the desktop's "Start/Programs/Sullivan City" menu. When the program starts up, it establishes a serial connection to the AS2 sensor over the com port specified in the system configuration file, starts collecting the five messages the sensor sends each time a vehicle is detected, and analyzes every fifth message received to determine if the vehicle can be classified as large and requires the extension of the green time. As we mentioned earlier, the AS2 sensor sends 5 messages for every vehicle it detects. The fifth message is sent after the vehicle clears the sensor area completely and it contains all the data parameters for the vehicle detected. The fifth message is saved by the AS2.exe program into a daily log file that conforms to the naming convention: "month_day_year.as2."

The AS2.exe program displays a message in a window on the industrial PC desktop every time a large vehicle is detected and requires the green time extension. The message includes: a time stamp, vehicle height, vehicle length, vehicle speed, and the number of seconds the green time was extended. The system also displays a warning message of potential problems with the sensor if it did not receive any messages from the sensor for a continuous five minute period. The five minute period parameter is configurable by the user and can be changed in the system configuration file "Truck.ini."

5.1.2 The TCC.exe Software Program

The TCC.exe program monitors the TCC classifier. To start the program, double click on the TCC shortcut icon on the industrial PC desktop. The program can also be started by selecting the TCC option from the desktop's "Start/Programs/Sullivan City" menu. When the program is started, it establishes a serial connection to the TCC classifier over the com port specified in the system configuration file, starts receiving the messages generated by the classifier every time a vehicle is detected, and analyzes the messages received to determine if the vehicle detected is large and requires green time extension. Each message received from the TCC classifier is saved by the TCC.exe program into a daily log file that has the format "month_day_year.tcc."

The TCC.exe program displays a message in a window on the industrial PC desktop every time a large vehicle is detected and requires the green time extension. The message includes: a time stamp, vehicle length, vehicle speed, lane number, and the number of seconds the green time was extended. The system also displays a warning message of potential problems with the classifier if it did not receive any messages for a continuous five minute period. The five minute period parameter is configurable by the user and can be modified in the system configuration file "Truck.ini."

5.1.3 The AS2TCC.exe Software Program

The AS2TCC.exe program monitors the AS2 sensor and the TCC classifier together. To start the program, double click on the AS2TCC shortcut icon on the industrial PC desktop. The program can also be started by selecting the AS2TCC option from the desktop's "Start/Programs/Sullivan City" menu. When the AS2TCC program is started, it establishes a serial connection to both sensors over the com ports specified in the system configuration file. Then, it enters into an infinite cycle of checking the AS2 serial connection first for any data received from the AS2 sensor. If any vehicles were detected by the AS2 sensor, the program analyzes the data to identify large vehicles and if they require green time extension. The serial connection to the TCC classifier is checked next. If no large vehicles were detected by the AS2, the TCC data is analyzed to identify large vehicles requiring green time extension. However, if the AS2 detected a large vehicle that required the green time extension, the TCC data received is directly saved into the TCC daily log file without any analysis. The green time is extended once for any vehicle detected by both sensors. Data received from both sensors is saved into their respective daily log files. The AS2TCC.exe program displays a message whenever a vehicle detected by either system required extension of the green time. The program also displays a warning message when no data is received from either sensor for continuous five minutes. The format for the large vehicle detection and warning messages are the same as described in the previous two sections.

5.1.4 Remote Power On/Off Module

The system installed in Sullivan City includes a hardware device called Remote Power On/Off module. The Remote Power On/Off module enables the user to remotely shutdown the industrial PC and reboot it over the telephone.

The procedure to turn the power **OFF** remotely on the industrial PC follows:

- Dial the telephone number (210-485-1064), connected to the Remote Power On/Off module, and allow only one RING, then hang-up. This will disable the AUX port and "prime" the unit for two minutes."
- Dial the telephone number again immediately within 15 seconds of hanging up, and allow it to RING for at least 15 rings and hang up.
- The system will hang up within the next five minutes.

To turn the power on remotely on the industrial PC:

- Dial the telephone number (210-485-1064) and allow only one RING, then hang-up.
- Dial the telephone number again immediately within 15 seconds of hanging up, and allow it to RING at least five times, but no more than 10 times and hang up.
- The industrial PC will boot up within the next five minutes.

The Remote Power On/Off system consists of two hardware devices labeled the "Power On/Off + Aux" unit and the "Intelligent Power Module" unit. All the devices plugged into the power strip connected to the Intelligent Power Module will be shut down when the power is turned off remotely using the above described procedure. The industrial PC and the modem should always be plugged into the power strip connected to the Intelligent Power Module.

5.1.5 System Configuration Parameters

The system configuration file "Truck.ini" is located in the same subdirectory as the software programs, i.e., "C:\Sullivan\Apps," on the industrial PC. The Truck.ini file includes four sections of systems parameters. The first three sections specify the serial ports and serial communication parameters needed to connect to the three sensors, the AS2, the TCC, and the Sonic sensor, respectively. The serial port parameter is the only parameter in those sections that the user might need to modify anytime he changes the serial port a sensor is currently connected to on the back of the industrial PC.

The fourth section in the system configuration file includes the following parameters:

- AS2_MaxNoResponseTime: the maximum number of minutes that has to pass without receiving any data from the AS2 sensor before trying to reinitialize the sensor. A message will be displayed to warn the user of potential problems with the sensor.

- TCC_MaxNoResponseTime: the maximum number of minutes passing without receiving any data from the TCC classifier before attempting to reinitialize the device and warning the user of potential problems with the classifier.

- CutoffSpeed: the speed below which the green time would not be extended for large vehicles.

- MaxCallTime: the maximum number of seconds that the green time would be extended for large vehicles detected in succession before allowing the phase to turn to red.

- SpeedForExtension: the speed above which green time would be extended by 3.0 seconds for large vehicles.

- Extension1: the number of milliseconds green time would be extended for large vehicles traveling at speeds of 45 mph or above.

- Extension2: the number of milliseconds green time would be extended for large vehicles traveling at speeds lower than 45 mph but higher than 15 mph.