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16. Abstract

This research effort evaluated the use of inductance loop detectors in a freeway management situation to determine optimal speed trap distance, best wire type, shortest response time condition, and most accurate speed detection scenario. Five speed trap distances were evaluated with a variety of detector units. An optimal speed trap distance was not identifiable. However, the research consistently identified that the best method for obtaining accurate speeds requires the use of inductance loop detectors utilizing identical make and model detector units. The researchers also compared single conductor wire and multiconductor cable inductance loops for accuracy of speed measurement. It was found that the response times for multiconductor cable inductance loops are significantly shorter and more uniform than response times using loops formed with single conductor wire.

The response time from the presence of a vehicle at an inductance loop to the actual detection of a vehicle varies. As the response time varies, so does the accuracy of speed measurement. Vehicle size, vehicle speed, detector type, detector sensitivity, and inductance loop wire type all affect the response time. Measuring accurate vehicle speeds with inductance loop detector speed traps is dependent upon the vehicle mix, vehicle speeds, detector type, and detector sensitivity settings. While using a 9 meter (30 foot) speed trap, the speed difference between an inductance loop speed trap and an infrared light sensor speed trap was found to be very small for most cases. As speeds increased, the speed differences also increased. Finally, the Naztec Card Rack System was found to consistently measure the lowest speed differences for all conditions.

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SPEED MEASUREMENT WITH INDUCTANCE LOOP SPEED TRAPS

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IMPLEMENTATION STATEMENT

This research provides a more consistent basis for the application of inductance loop detectors by the Texas Department of Transportation and local governmental units in Texas. Inductance loop detectors are an integral part of most freeway management systems in use today. Since speed measurement is a major factor in the operation of freeway management systems, knowing both the optimal speed trap distance for accurate, effective speed detection by inductance loop detectors and the lag time between the presence of a vehicle at an inductance loop and its detection is very helpful in establishing more accurate speed measurement. Finally, an evaluation of various types of wire used in inductance loops will determine the best and most effective way to wire an inductance loop for speed measurement.

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of either the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. Dr. Donald L. Woods (P.E. #21315) was the Principal Investigator for the project.

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SUMMARY

Reducing congestion in our nation's urban areas has become a top priority of state departments of transportation nationwide. The development and construction of freeway management systems have recently begun to help reduce these problems. A major component of freeway management systems is the inductance loop detector. This research effort evaluated the use of inductance loop detectors in a freeway management situation to determine optimal speed trap distance, best wire type, shortest response time condition, and most accurate speed detection scenario.

Five different speed trap distances (from 6 to 24 meters [20 to 80 feet]) were evaluated with a variety of detector units. An optimal speed trap distance was not identifiable, but research and practical considerations point to 9 meters (30 feet) as being the best trap length. The research consistently showed that accurate speed measurements cannot be made using different models of detector units. In order for speed measurements to be accurate, the change in inductance required for detection must be very similar between detector units. Identical make and model detector units easily meet this criteria. The error measured for speed traps with identical detector units averaged about 2.4 km/h (1.5 mph) for all speeds, while errors for speed traps with different detector units varied widely from 1.6 to 194 km/h (1.0 to 120 mph). Clearly, the best method for obtaining accurate speeds with inductance loop detectors utilizes identical make and model detector units.

Single conductor wire and multiconductor cable inductance loops were compared for accuracy of speed measurement. The speed difference, i.e., the difference in speeds measured using a multiconductor cable inductance loop and an infrared light sensor speed trap was only 0.224 km/h (0.139 mph). On the other hand, the speed difference using a single conductor wire speed trap was about 10 km/h (6 mph). Clearly, the best method for obtaining accurate speeds with inductance loops utilizes multiconductor cable loops.

The response time, the time difference in the arrival of a vehicle at an inductance loop and the actual detection of a vehicle, varies. As the response time varies so does the accuracy of speed measurement. Vehicle size, vehicle speed, detector type, detector sensitivity, and inductance loop wire type all affect the response time. The shortest response times were found to occur when using the Naztec card rack detector. The multi-conductor cable loops also had shorter response times than did the single conductor wire loops.

Measuring vehicle speeds accurately with inductance loop detector speed traps is dependent upon the vehicle mix, vehicle speeds, detector type, and detector sensitivity settings. While using a 9 meter (30 foot) speed trap, the speed difference between an inductance loop speed trap and an infrared light sensor speed trap was found to be very small for most cases. As speeds increased, the speed difference also increased. Finally, the Naztec Card Rack System was found to consistently measure the lowest speed differences for all conditions.

1.0 INTRODUCTION

The prevalence of congestion on virtually every major roadway in metropolitan areas has prompted transportation agencies to consider adopting some form of traffic management system. Traffic management systems are designed around a comprehensive data base which will facilitate proactive decisions on the control and routing of traffic to lessen the impact of congestion on the movement of people, goods and services. An integral part of a traffic management system is the technology and equipment for monitoring traffic and recording traffic data. The measurement of traffic speeds is very important. There are several means of measuring traffic speeds, and most of them involve measuring the time that a vehicle requires to travel between two detection points, commonly referred to as a trap. These traps are usually formed using inductance loop detectors (ILD). The ILD has the advantage of being relatively inexpensive while providing versatility in measuring other traffic characteristics such as volume, density and vehicle types.

The inductance loop is simply an electrical wire placed in the pavement in the form of a loop. The inductance loop generally has about three turns of wire, and is usually in the form of a square, about 2 meters on the side. Also, it can be in the form of a rectangle or a diamond. The loop requires an electronic device known as a detector unit to power the loop. The detector unit sends an alternating electrical current (A.C.) through the wire loop. The current produces an electromagnetic field about the loop in and above the roadway. When a vehicle passes through the electromagnetic field, energy is taken from the loop resulting in a change of inductance and a resulting frequency change in the loop. If the change in inductance is greater than a pre-set threshold value, the passing vehicle is "detected." Detection means that the detector unit will transmit an electronic pulse of 100 to 150 milliseconds in another circuit as a result of the change in inductance. Thus, ILDs can be used to count vehicles, and when two loops are placed a known distance apart, they can measure the time of passage between two loops, thus permitting the determination of the speed of the vehicle.

1.1 PROBLEM STATEMENT

In the past, ILDs have been used in conjunction with actuated traffic signals to provide arrival and presence information for more efficient intersection control. Now that congestion management and other traffic management systems are becoming reality, there is a new perspective of performance requirements imposed on detection systems. In addition to counting vehicles and registering vehicle presence, the detectors must respond in a precise timely manner so that they may be used in measuring or computing speeds. To obtain accurate time measurements to facilitate accurate speed trap computations, the detectors must register the arrival of a vehicle at a specific response time. The constraints on accuracy are amplified further by the high speeds that are characteristic of freeway operations. Major decisions will be made in the control and operation of large volumes of vehicles, and therefore speed computations must be accurate.

Three factors affecting the accuracy of speed detection are the optimal distance between two loops in a speed trap, the type of wire used to form the loop, and the response time of the loop. An optimal spacing is a spacing that is sufficiently long to provide accuracy in trap computations but not so long that drivers could change lanes before completing the loop. Also, there is a minimum distance at which crosstalk, or adjacent loops interfere with each other. Previous research indicates that crosstalk is likely to occur at a six meter spacing. Different wire types, and particularly the manner in which the wire loop is formed, produces different magnetic fields which affect the operating characteristics of ILDs. The inductance loop speed trap distance used in computing speed changes as response time increases and decreases. Consequently, accurate speed detection is dependent upon the speed trap distance, the detector response time and the type of wire loop.

1.2 OBJECTIVES/SCOPE

The primary objectives of the research were to experimentally determine 1) the optimal distance between two loops in a speed trap, 2) the best wire type (multi-conductor versus single stranded) for ILD operations, 3) the response time for an ILD to detect a vehicle, and 4) the accuracy of speed measurement by ILDs under various operating conditions. The scope of this research involved evaluating speed traps with distances of 6, 9, 15, 18, and 24 meters (20, 30, 50, 60, and 80 feet), and inductance loops constructed of single strand wire and multi-conductor wire. All data were collected at an experimental site located at the Texas A&M University Riverside Campus.

1.3 ANTICIPATED BENEFITS

This research provides a more consistent basis for the application of inductance loop detectors by the Texas Department of Transportation and local governmental units in Texas. Inductance loop detectors are an integral part of most freeway management systems in use today. Since speed measurement is a major factor in the operation of freeway management systems, the optimal speed trap distance for accurate and effective speed detection by inductance loop detectors is very helpful. The lag time between the presence of a vehicle at an ILD and the detection of a vehicle will also be very helpful. This will allow more accurate speed measurement. Finally, an evaluation of various types of wire used in inductance loops will determine the best and most effective way to wire an inductance loop for speed measurement.

2.0 BACKGROUND

Although inductance loop detectors have been used in the freeway environment over the last decade, few studies have been performed to determine the accuracy of detection for speed measurement of vehicles at high speeds. For the most part, inductance loop detectors have been used in lower speed conditions on city streets near traffic signals. Therefore, most of the research has been with regard to the capabilities of ILDs in that situation. The freeway environment is totally different than the city street environment. Consequently, the literature review focused on the characteristics of inductance loops, variations in detector units, the effects of speed and vehicle size, detector lag time, and speed trap distance, as they apply to the freeway environment.

2.1 INDUCTANCE LOOP DETECTOR PROPERTIES

The flexibility in the loop detector design allows for a broad range of vehicle detection (1). Even though inductance loops can be designed many different ways, the basic element is an insulated electrical wire placed in a saw cut in the road surface. An electrical current is sent through the loop wire by attaching the inductance loop to a power source, normally a detector unit (or amplifier), thus creating an electromagnetic field. The loop becomes the inductive element of the circuit. The Electronic Engineers and Technicians Reference Handbook defines *inductance* as "the property of a circuit element which tends to oppose any change in current through it." (2, pg. 123) The inductance in the loop wire is based on the wire size, wire length, the number of wire turns, and the amount of insulation surrounding the wire. After the loop wire has been buried in a stable pavement and an electromagnetic field is created, passage of a vehicle through the loop will reduce the energy in the system causing a decrease in the inductance. The tuned radio frequency circuit is changed as a result of the change in inductance, resulting in detection of the vehicle (3).

Other elements, such as weather, loop placement, and wire size may affect the operating characteristics of inductance loop detectors. Extreme heat or extreme cold weather might affect the ability of an inductance loop to operate properly. In the past, it was believed that water had a detrimental effect on the operating ability of inductance loops. In a study conducted at the Texas Transportation Institute in the summer of 1992 where an inductance loop was flooded with water and then tested, it was determined that water did not adversely affect inductance loop detector operations (4).

Inductance loops can be placed either on the surface of the roadway, buried just beneath the surface, or buried deep, 510 mm (20 inches) into the pavement. Obviously, a buried loop will have a longer life span and is therefore used more often than a surface loop. The problem with a deep buried loop is that sometimes small vehicles or motorcycles can go undetected due to the small magnitude of the electromagnetic field that the vehicle is able to change. In a Texas

Transportation Institute study it was found that for a large car the surface loop had a percent 1.726% change in inductance, while the deep buried loop only changed 0.201% (5). In most cases, this level of percent change is sufficient to exceed the threshold set in the detector unit, but it is evident that the depth at which a loop is placed affects the operating ability of an inductance loop detector.

Another factor affecting the operation of inductance loop detectors is the type of wire being used in the inductance loop. Generally, most inductance loops are formed by wrapping a single strand of wire around the loop shape for the prescribed number of turns. As these turns are placed in the saw cut, they are randomly spaced relative to the other wire turns. Variable spacing of the wires in the loop will result in a variable electromagnetic field. On the other hand, a multi-conductor cable can be used, and due to its construction, it will hold the wire loops in close proximity to each other. This should permit a more uniform magnetic field that will provide more accurate detection.

There are several problems associated with using multi-conductor cable that should be noted. First, a wider saw cut in the pavement must be used to place the cable. Multi-conductor cable requires an 8.0 mm (5/16 inch) saw cut, while single strand wire requires a 6.25 mm (1/4 inch) saw cut. This will require a larger saw blade at a higher cost, and the use of more loop sealant. If the operation of multi-conductor cable is significantly better than single strand wire, it would be advantageous to use multi-conductor cable.

2.2 DETECTOR UNITS

The inductance loop detector (commonly called an amplifier) operates in two different modes, presence or pulse. Presence mode will hold a signal from the loop for as long as a vehicle is over the loop. This mode is commonly used for traffic signal approaches to determine the presence and departure of right-turning vehicles. If a right-turning vehicle departs the intersection during the red phase, and no other vehicles have approached the intersection, the call to the traffic signal will be canceled due to the departure of the vehicle, and the signal will not need to be switched to green to allow the vehicle to move through the intersection. In the pulse mode, the detector transmits a pulse, registering notice of arrival of a vehicle with the traffic control unit. That call will remain in the memory of the control unit until some disposition is made by the control unit, regardless of the actual departure of the detected vehicle. Vehicle counts are commonly conducted using pulse mode. Many different kinds of detector units are available. Two such detectors are the traditional single unit detector and the rack-mounted detector system. The single unit detector uses one unit for every inductance loop and all units are powered separately. The rack-mounted detector system utilizes circuit cards that contain two or four detectors per card with a variable number of cards per system. The cards are all powered by a single source. The rack-mounted detector system is cheaper than the single unit detectors, for the same number of detectors, but to date no studies have tested the accuracy level of single unit detectors versus rack-mounted detector systems. The rack-mounted detector system should

provide an economic advantage if its operation equals or exceeds that of the standard single unit detectors.

2.3 EFFECTS OF SPEED

Recent studies performed at the Texas Transportation Institute have produced valuable information on the operational limits of ILDs not previously a part of the research literature (4,5,6,7,8,9). Many of these studies dealt with the varying percent change in inductance in the loop dependent upon the operating conditions. For instance, in one study it was determined that for a vehicle traveling at 32 km/h (20 mph) a 3% shift in inductance occurred, while at 129 km/h (80 mph) only a 1% shift in inductance occurred (5). Figure 1 illustrates the findings for large cars and small cars with respect to inductance change with a change in speed. The normal variability of an ILD is considered to be about 1%. Therefore, it would be feasible to conclude that a vehicle traveling at 129 km/h (80 mph) could go undetected. This is of great concern when ILDs are to be used in the high speed freeway environment. It is quite likely that vehicles will travel at speeds of 113 to 129 km/h (70 to 80 mph) even though the speed limit is only 105 km/h (65 mph) on freeways.

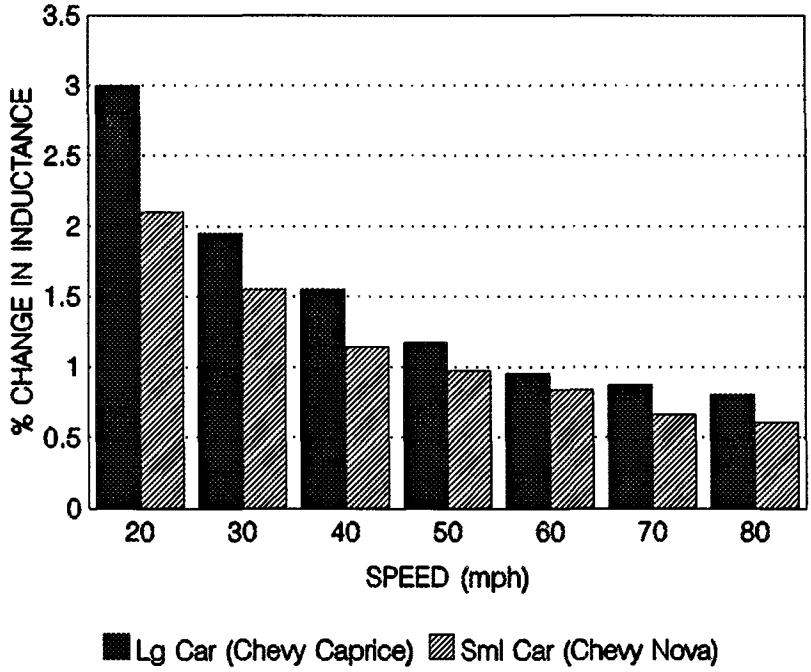

Figure 1. Variation of Inductance with a Change in Speed
Note: 1 mile per hour = 1.6 kilometers per hour.

2.4 EFFECTS OF VEHICLE SIZE

Because vehicles of various sizes use the freeways, it is important to determine if ILDs can accurately measure speeds of all vehicle types. Past studies have shown that different vehicles will produce inductance changes (5). It is important to determine if that difference will significantly affect speed measurement of various sized vehicles.

2.5 DETECTOR RESPONSE TIME

Another aspect of ILD operation is the response time of the detector, the time that a vehicle is present over the loop, but has not been detected. To accurately measure speed, the exact distance over which the speed is being measured must be known. If the response time varies for each detector, the distance used to measure speed will change because the vehicle will be at a different position with respect to the loop measurement point. The smaller the response time, the smaller the chance of error in the speed measurement.

There is always a response time associated with the operation of detectors. Thus, it is essential that this response time be minimized and be consistent at both ends of the speed trap. For this reason, it is important that identical detectors be used to form a speed trap.

2.6 SPEED TRAP DISTANCE

Another aspect of speed measurement is the speed trap distance used with the ILD. The Federal Highway Administration's Traffic Detector Handbook noted that the normal speed trap distance is 5 meters (16 feet) (1). On the other hand, speed traps in the United Kingdom are normally operated at 2 meters (6.5 feet) (3). In the United Kingdom study it was noted that the most important factor in measuring speeds is maintaining identical loops. In previous studies at the Texas Transportation Institute speed trap distances of 3 and 6 meters (10 and 20 feet) were studied. The first study showed that 3 meter (10 foot) traps cause too much crosstalk between the inductance loops (8). Crosstalk occurs when the magnetic fields between two loops are too close and the fields overlap. This will cause ILDs to detect vehicles too early or continue the detection when there is no vehicle present. In a follow-up study on crosstalk between loops it was determined that crosstalk also occurs between loops at 6 meter (20 foot) spacing (10). Crosstalk is a serious problem and will easily result in erratic and undependable speed measurements. The separation distances examined in this study ranged from 6 to 24 meters (20 to 80 feet) so that an optimal spacing may be observed.

3.0 STUDY DESIGN

This study was designed to evaluate the aspects of detector spacing (trap length), wire type and size, and detector response time in the ILD speed traps. The research for this study was conducted at two experimental sites on the concrete runways at the TTI facilities located at the Texas A&M University Riverside Campus.

3.1 CONSTRUCTING THE TESTING SITE

One test site consisted of four 1.8 meter by 1.8 meter (6.0 foot by 6.0 foot) inductance loops on a concrete runway. The ILDs were located 5 meters (15 feet) from the edge of the pavement in the center of a 3.8 meter (12.5 foot) wide panel, as shown in Figure 2. The loop itself was cut into the concrete pavement. All the saw cuts were 50 mm (2 inches) deep, with the width of the cut varying from 6.25 mm (1/4 inch) to 12.5 mm (1/2 inch) depending on the type of wire used. The loops were spaced 6, 15, and 24 meters (20, 50, and 80 feet) apart measured from the front edge of one loop to the front edge of the next loop. From the edge of the pavement, the loop wire ran underground through a 25 mm (1.0 inch) diameter PVC pipe to the pullbox.

A #12 THHN copper wire was used to form loops A, B, and C. The first three loops were constructed using 3 complete turns and then 3 additional individual turns, each coming out to the pull box. This allowed for each loop to be tested with 3, 4, 5, and 6 turns of wire. Loop D was constructed similarly, except it used a 6-conductor unshielded cable, described as 3 pair, #18 AWG, AWM Style 2464. Connections could be made in the pull box to form up to six turns using the multi-conductor cable. Permanent Sealer 974 sealed the loops permanently into the saw cuts.

A second test site at the Texas A&M University Riverside Campus was constructed in order to test two loops using multi-conductor cable at a 9 meter (30 foot) spacing. Two 1.8 meter (6 foot) square loops were cut into the pavement in the center of a 3.8 meter (12.5 foot) wide panel that was located 4.5 meters (15 feet) from the edge of the pavement. Each loop is 50 mm (2 inches) deep and 8.0 mm (5/16 inch) wide. A multi-conductor cable, consisting of four #12 AWG, stranded conductors, unshielded, type THHN/THHW, was placed in each loop and sealed with Permanent Sealer 974 sealant. Connections to the testing equipment were made in the pull box and soldered to insure solid connections.

To measure response time, light sensors were placed directly over the leading edge of the loops. A vehicle passing through the system will cross the light sensors and the loops, and thus, the response time of the detectors could be measured. Also, the speed measurement by loop detectors could be compared to measurement by infra-red sensors.

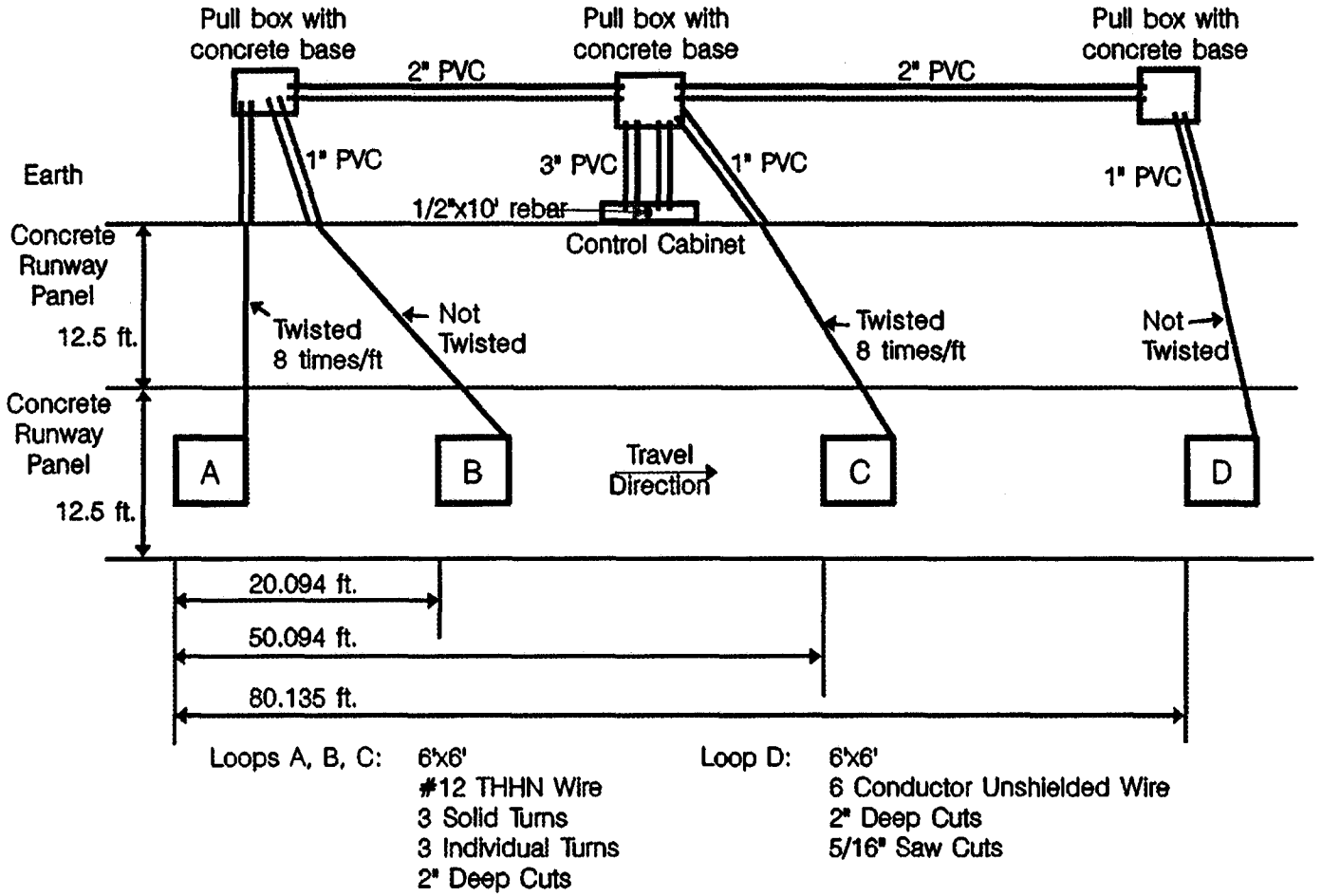

Figure 2. Test Site Number 1

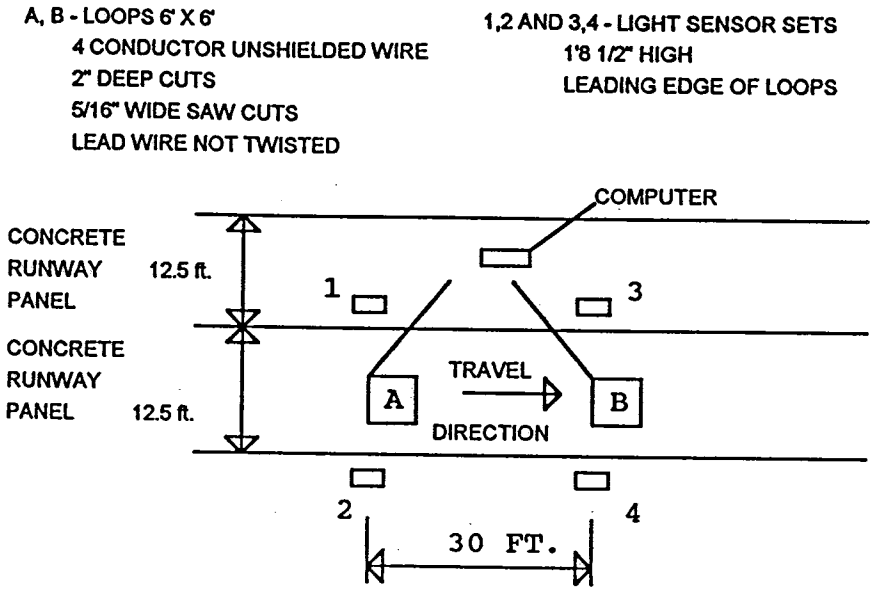

Figure 3. Test Site Number 2
Note: 1 inch = 2.54 centimeters and 1 foot = .3048 meters

The output from all of the ILDs and light sensors were connected to a computer. A computer program marked the onset and offset of all detectors and light sensors with respect to time. These time measurements were used to determine the speed of passing vehicles.

3.2 EVALUATION OF SPEED TRAP DISTANCE

Five design vehicles were used for evaluation of speed trap distance (see Table 1).

Table 1. Classification of Design Vehicles

Classification	Vehicle	Height Above Pavement	Vehicle Length	Front Vehicle Width
Small Car	1987 Honda Civic	225 mm (9")	3.9 m (12' 10")	1.6 m (5' 1")
Large Car	1991 Ford Crown Vict.	213 mm (8.5")	5.3 m (17' 3")	1.9 m (6' 3")
Pickup Truck	1988 Chevy S-10 Longbed	225 mm (9")	5.1 m (16' 9")	1.6 m (5' 4")
Motorcycle	1982 Suzuki 3006SL	184 mm (7.25")	2.1 m (6' 9")	0.5 m (1' 6")
High Profile Truck	Kenworth Tractor-Trailer	1263 mm (50.5")	16.5 m (54' 2")	2.4 m (8' 0")

Test site number one was used. Speed traps with distances of 6, 9, 15, 18, and 24 meters (20, 30, 50, 60, and 80 feet) were tested with all four detector units and 3 turns of wire. Every test vehicle made five to ten passes over the speed traps for all combinations of sensitivity level and detector unit. An on-site computer recorded the time that each of the four detectors went on and off to the nearest millisecond. The speed of each test run was verified by a radar gun and compared to the speed predicted by the pair of ILDs. Completion of this series of tests provided input for the determination of the optimal speed trap distance and appropriate sensitivity level for accurate speed detection in a freeway management system.

3.3 EVALUATION OF WIRE TYPE

To determine what type of wire provides the highest level of accuracy, multi-conductor wire loops and single strand wire loops were tested. Three 9 meter (30 foot) speed traps were available for testing. The first speed trap had two loops constructed of single stranded wire. The second speed trap had one loop with multi-conductor cable and one loop with single strand wire. The third speed trap had two loops constructed of multi-conductor cable. Each loop was tested by driving a large car over each speed trap twenty times at 65 km/h (40 mph). The detector units were set with the same sensitivity and frequency levels. The inductance loops consisted of three turns of wire. Finally, no other loops were operating at the same time to insure that crosstalk between loops did not occur. Completion of this task provides valuable information on the most effective wire type to be used for speed measurement with ILDs.

3.4 EVALUATION OF RESPONSE TIME

While performing the speed measurement studies, the response time for the inductance loops was recorded. A light sensor adjusted to the vehicle bumper height was placed directly over the leading edge of the inductance loop. The time from when the light sensor came on until the time that the inductance loop came on was the response time.

Five test vehicles were used in this study: a large car, a small car, a pickup truck, a motorcycle, and a high profile truck. Detector Systems Digital Loop Detector Model #813-103SS detectors with low, medium, and high sensitivity settings were used. Each vehicle made five passes over the loops at speeds ranging from 32 to 129 km/h (20 to 80 mph) for all three sensitivity settings. Different kinds of loops were also tested in this series: single strand wire loops and multi-conductor wire loops. The results from this task provided information on the operating characteristics of ILDs that have never before been collected.

3.5 EVALUATION OF SPEED MEASUREMENT

The speed measurement study was conducted using two different types of detector units. The first study used two identical Detector Systems Digital Loop Model #813-103SS Detectors. The second study used the Naztec Card Rack System Model 722-Tx/I detector. Three different sensitivity settings were used on each detector: low, medium, and high. The corresponding sensitivity levels were determined from a previous study at Texas A&M University that compared the sensitivity levels for each detector (10). Table 2 illustrates the corresponding sensitivity settings. All tests were run at medium-high frequency. The same five test vehicles used in the evaluation of speed trap distances part were used (see Table 1). The large car, small car and pickup truck each made five passes over the loops for each speed with speeds ranging from 32 to 129 km/h (20 to 80 mph) for all three sensitivity settings. The motorcycle and the high profile

truck testing did not include the 129 km/h (80 mph) test. Finally, the inductance loop was tested using three turns of wire only. Completion of this series of tests provided valuable information on the speed measuring capabilities of ILDs under various operating conditions.

Table 2. Comparison of Detector Sensitivity Settings

Detector Sensitivity	Detector Systems Detector		Naztec Detector System	
	Sensitivity Setting	Average Percent Change In Inductance	Sensitivity Setting	Average Percent Change In Inductance
Low	2	0.28	3	0.364
Medium	4	0.045	6	0.061
High	6	0.017	8	0.015

4.0 OPTIMAL SPEED TRAP DISTANCE RESULTS

When speed traps are to be formed using induction loop detectors, there is likely to be an "optimal" spacing of those loops. These loops should be spaced far enough apart that they won't talk to each other, and so that time measurement accuracy will be sufficiently precise to yield reasonably accurate speeds. Similarly, the spacing should be kept reasonably short to reduce the likelihood that a vehicle can change lanes into or out of the loop trap, thus missing one of the loops. The trap length must be short enough to result in time headway between successive vehicles producing unrealistic speeds that will be screened out by the software. For example, a two second time headway in a 9 meter (30 foot) gap would result in a speed computation of 16.2 km/h or 10 mph. Such a low speed in a freeway setting would trigger the software to reset itself for the next vehicle entering the trap. Also, it is important that the trap be short enough to avoid the possibility of the trap being occupied by two vehicles simultaneously.

This portion of the study dealt with the accuracy of measurements as affected by the length of inductance loop speed trap. The study evaluated five different speed trap lengths in order to determine the optimal separation distance for measuring speeds.

4.1 EVALUATING SPEED TRAP DISTANCE WITH PASSENGER CARS

Four different models of detectors, two Detector Systems models, labeled A and B, and two Sarasota models, labeled C and D, were utilized in evaluating the five different speed trap distances provided by the experimental test site at the Texas A&M University Riverside Campus. Speed trap distances of 6, 9, 15, 18, and 24 meters (20, 30, 50, 60, and 80 feet) were evaluated. Six different traps were evaluated, with two of them being 9 meters (30 feet). All six speed traps were tested with three turns of wire and a low sensitivity level.

Beginning with the large car, ten passes were made over the loops at speeds of 32, 65, 97, and 129 km/h (20, 40, 60, and 80 mph). The on/off times of each detector were recorded by the computer and later evaluated in a spreadsheet. The resulting calculated speeds for each run were compared to the actual speeds observed by radar, producing a speed estimation error in miles per hour. The average of the estimation error for a set of ten runs was calculated, along with the standard deviation, for comparison purposes. These values are listed in Appendix B. The average error in miles per hour was determined for each of the six trap distances and plotted against speed, as shown in Figure 4.

Figure 4 indicates that trap distances of 6, 15, and 24 meters (20, 50, and 80 feet) yielded the largest errors. The error at 129 km/h (80 mph) for the 6 meter (20 foot) trap distance approaches 194 km/h (120 mph). The trap distances of 9 and 18 meters (30 and 60 feet) yielded the least error, and, in fact, a negative error, indicating that the calculated speed is slightly under

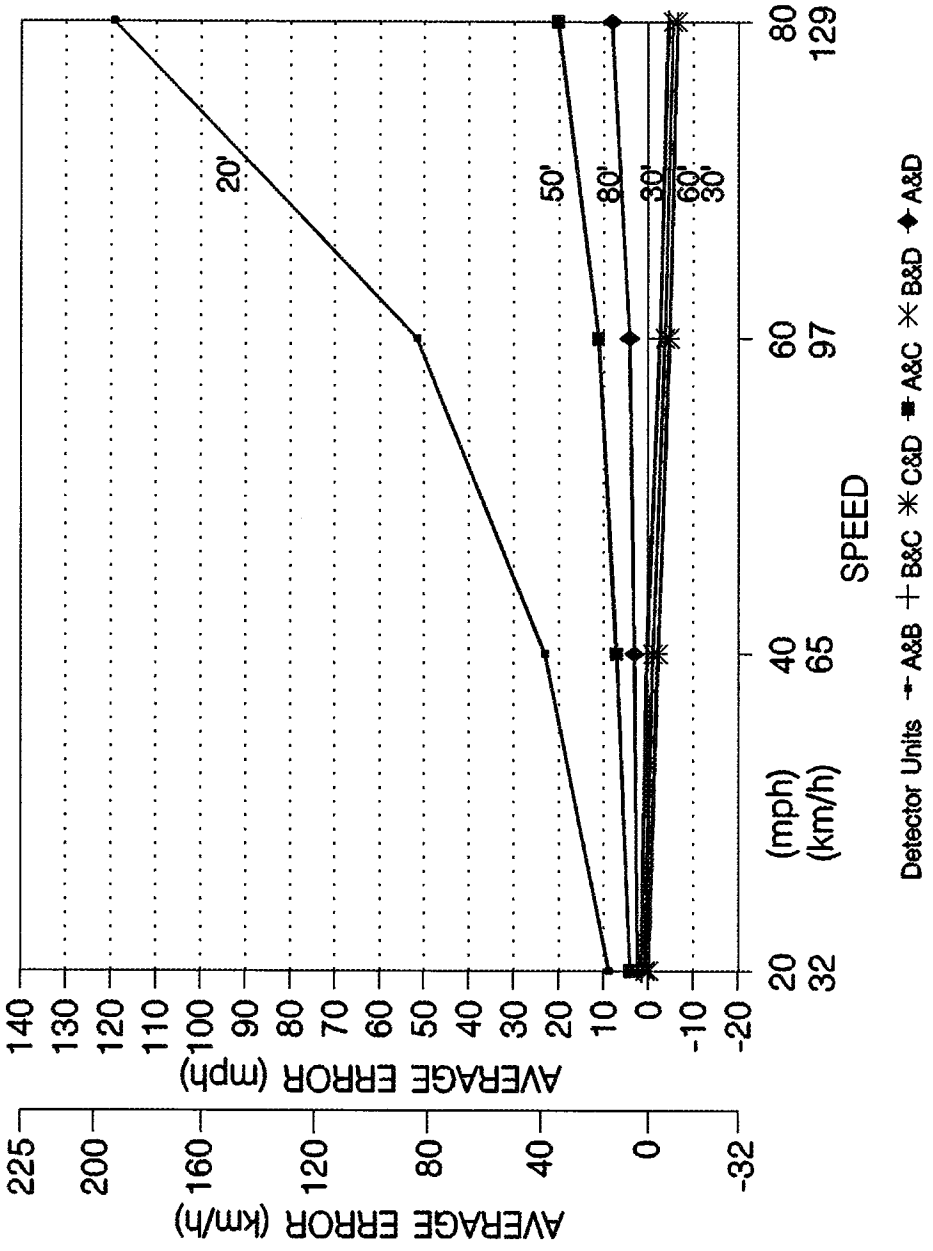

Figure 4. Average Error for Different Speed Trap Lengths for a Large Car

the actual speed. Therefore, the figure seems to indicate that trap spacings of 9 and 18 meters (30 and 60 feet) are best, with the worst trap distance being 6 meters (20 feet). The pickup truck yielded similar results, as indicated in Figure 5.

4.2 EVALUATION OF DETECTOR UNIT ORDER

Under closer review, both figures show an unusual and suspicious pattern. The three trap distances with large positive errors were all tested using Detector Systems detector unit A. Since these three trap distances do not appear to follow the same pattern as the other three trap distances, a malfunction was suspected to have occurred with detector unit A. To test this new theory, both the large car and pickup truck test runs were repeated, but this time the detector units were placed in a different order. The resulting average errors for each trap distance and speed are shown in Figures 6 and 7, for the large car and pickup truck, respectively, and the resulting data are listed in Appendix B.

With the detector units in a different order, different results were achieved for all trap distances. Now, the two speed traps with the largest average error are the 9 meter (30 foot) speed traps, but one of these did not use detector unit A. In addition, the 6 meter (20 foot) trap, which was the worst case before, is now one of the best cases, with an average error of only about 16 km/h (10 mph) at speeds of 129 km/h (80 mph). The two best cases, the 18 and 24 meter (60 and 80 foot) trap distances, both utilized detector unit A. Therefore, the poor results of the first series of tests apparently were not due to a malfunction with detector unit A. Obviously, not all detectors have the same performance characteristics.

These results indicate that using multiple brands of detectors will create uncertain conditions about the accuracy of the speed estimates. Each detector brand and model has different threshold values for low, medium, and high sensitivity levels, as identified for three of the models in Table 3. Because of the differences in sensitivity threshold, each detector indicates a detection as the vehicle passes a different position in the loop. Therefore, the speed estimations which are based on these on/off times will not be very accurate. At slow speeds, the error is not very large because the vehicles are on the loop longer and the on/off times of the detector unit are spread further apart. As vehicle speeds increase, the error increases due to the different threshold values of the sensitivity levels. Thus, this study indicates that accurate speeds can be calculated from a pair of inductance loop detectors only if identical detector units are used, and they are set at identical sensitivity level threshold values.

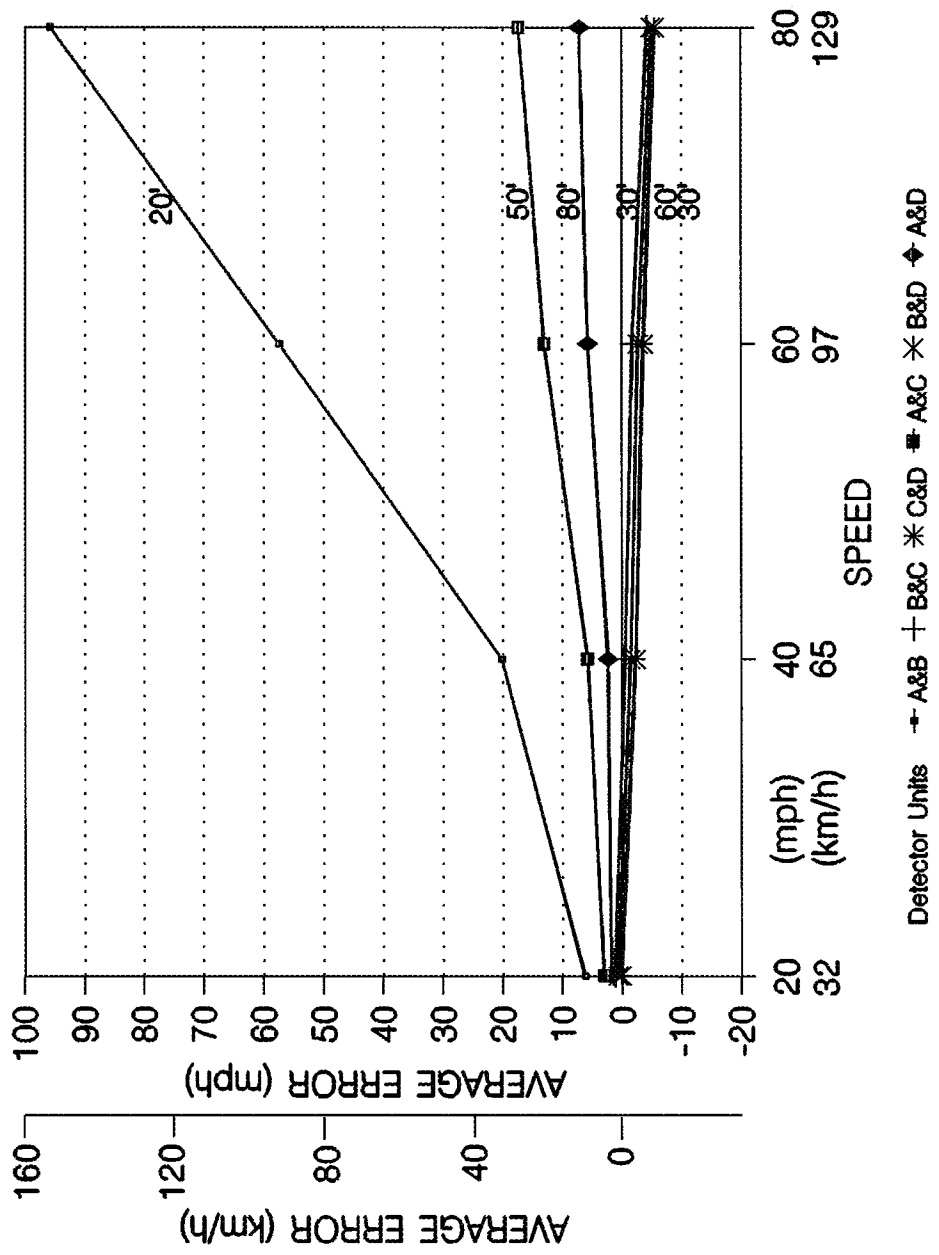

Figure 5. Average Error for Different Speed Trap Lengths for a Pickup Truck

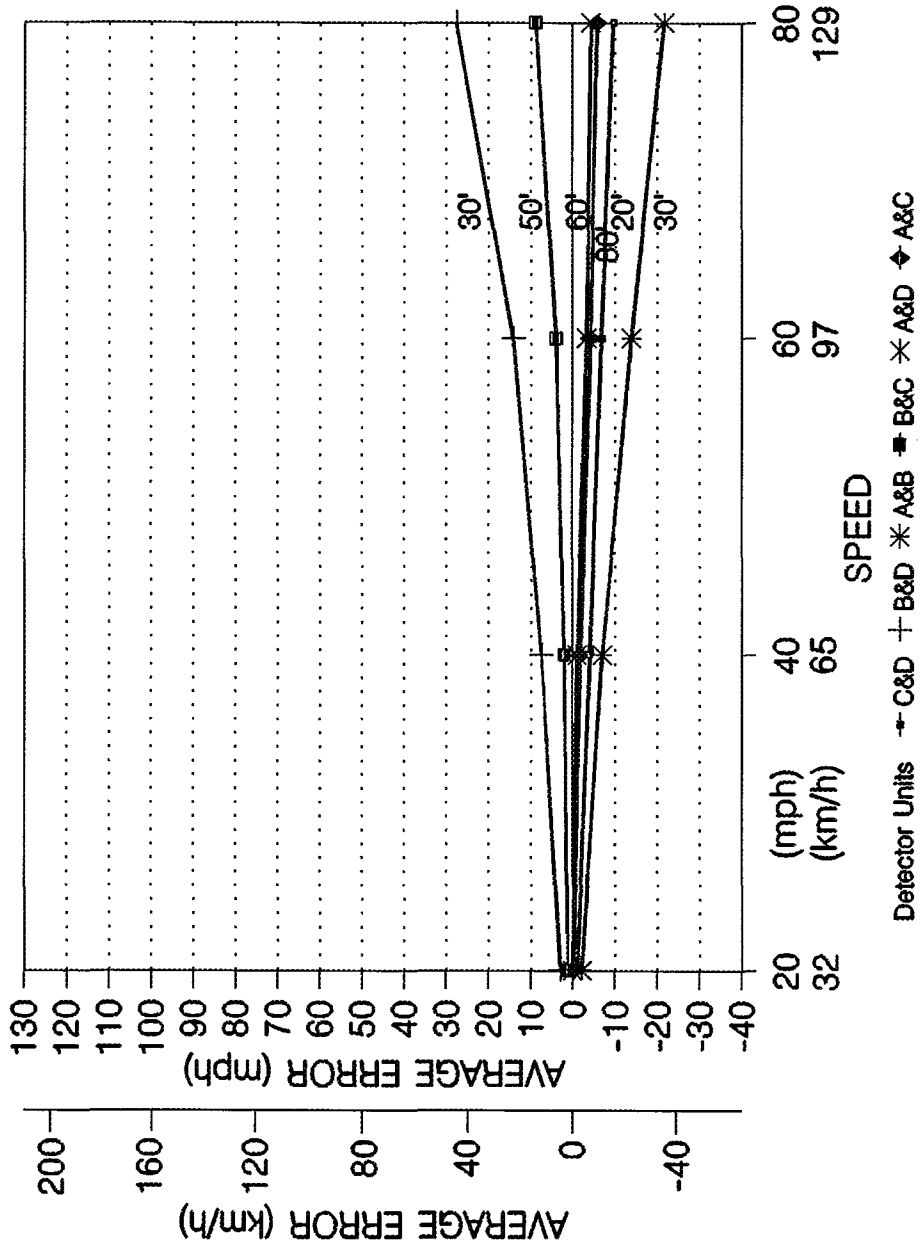

Figure 6. Average Error for Different Speed Trap Lengths for a Large Car and a Different Detector Order

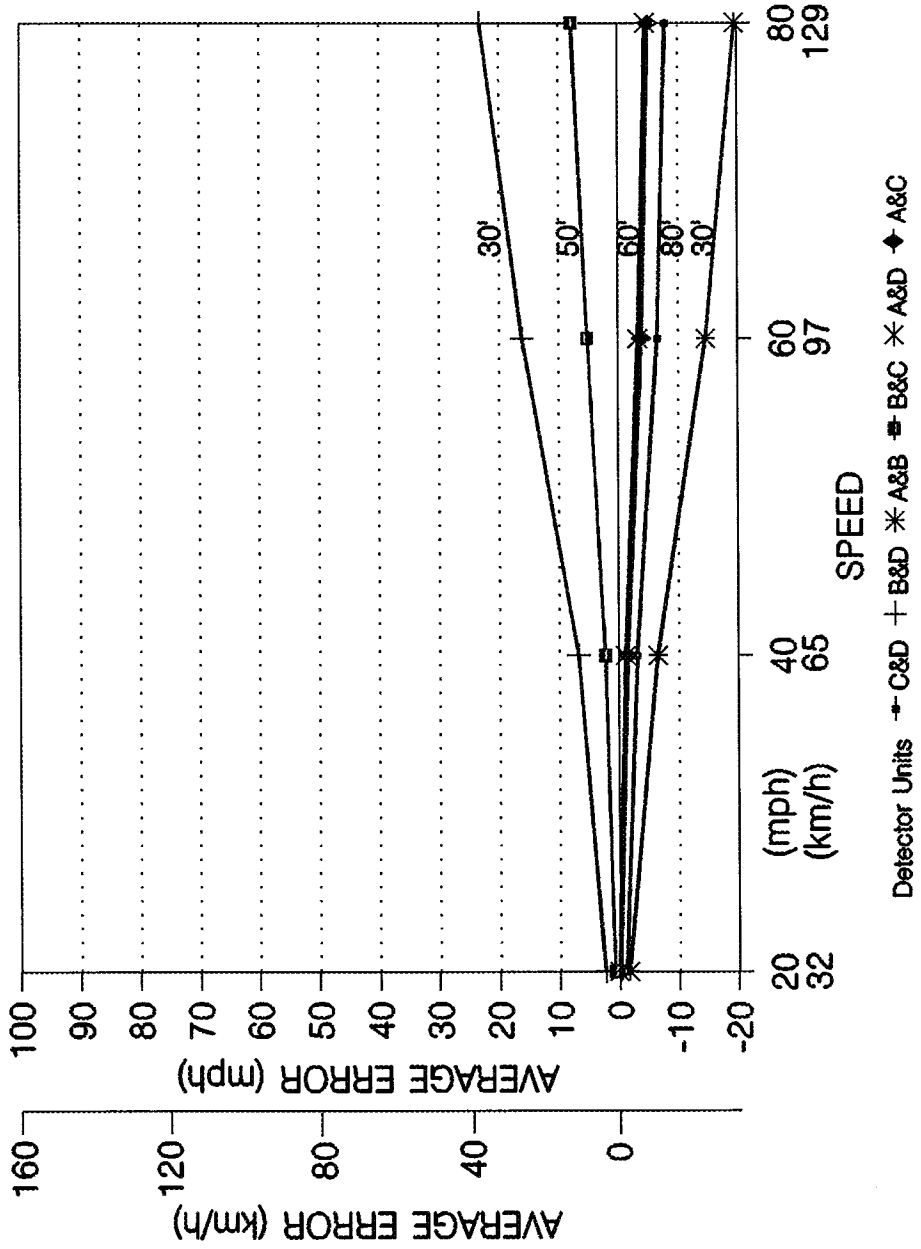

Figure 7. Average Error for Different Speed Trap Lengths for a Pickup Truck and a Different Detector Order

Table 3. Percent Change in Inductance Required for Vehicle Detection at Various Sensitivity Levels

Detector Model	Low Sensitivity	Medium Sensitivity	High Sensitivity
Detector Systems 102SS	0.18	0.047	0.015
Detector Systems 103SS	0.28	0.074	0.020
Sarasota 515TX	0.15	0.048	0.011

Another factor which may have contributed to some of the error is that the fourth loop in the series was a 6-conductor cable and not the standard 12 gauge wire which was used to form the remaining three loops. However, without identical detectors, it is uncertain whether or not the difference of the fourth loop had any effect on the accuracy of the speed calculations. In addition, the radar speed meter which measured speed to the nearest one mph could possibly cause an error of ± 0.8 km/h (± 0.5 mph) for each vehicle run.

4.3 DETECTION USING IDENTICAL DETECTORS

To test the theory of identical detectors, four new Detector Systems brand detector units were purchased. The identical model detector units were tested on low sensitivity for both the large car and the pickup truck. By using these vehicles, a direct comparison could be made with the data previously collected using different brands and types of detectors. The average error for each speed was determined for each trap in the same manner as discussed previously. The resulting plots for the large car and pickup truck are shown in Figures 8 and 9, respectively.

Figure 8 shows that the use of identical detector units dramatically reduces the average error for all speed trap lengths. Average errors for all trap lengths are less than 2.4 km/h (1.5 mph) for speeds of 32, 65, and 97 km/h (20, 40, and 60 mph). At 129 km/h (80 mph), the average error ranges from 2.4 km/h to 7.3 km/h (1.5 to 4.5 mph). This is a tremendous improvement over using different models of detector units, where the average error ranged anywhere from -16 to 194 km/h (10 to 120 mph). Figure 9 shows that test data for the pickup truck indicates slightly larger errors than for the large car, but the average errors are still substantially lower than those measured using different detector units.

This part of the study has shown that speed measurements are reasonably accurate at all trap lengths of 6 to 24 meters. It did, however, show conclusively that identical detectors and sensitivity settings are essential for accurate speed measurements. From these findings and the lane changing and crosstalk constraints discussed earlier, the "optimal" speed trap length is 9 meters. Certainly longer traps may be used successfully, but the engineer should be cognizant of the higher probability of errant data due to lane changing as the trap length is increased.

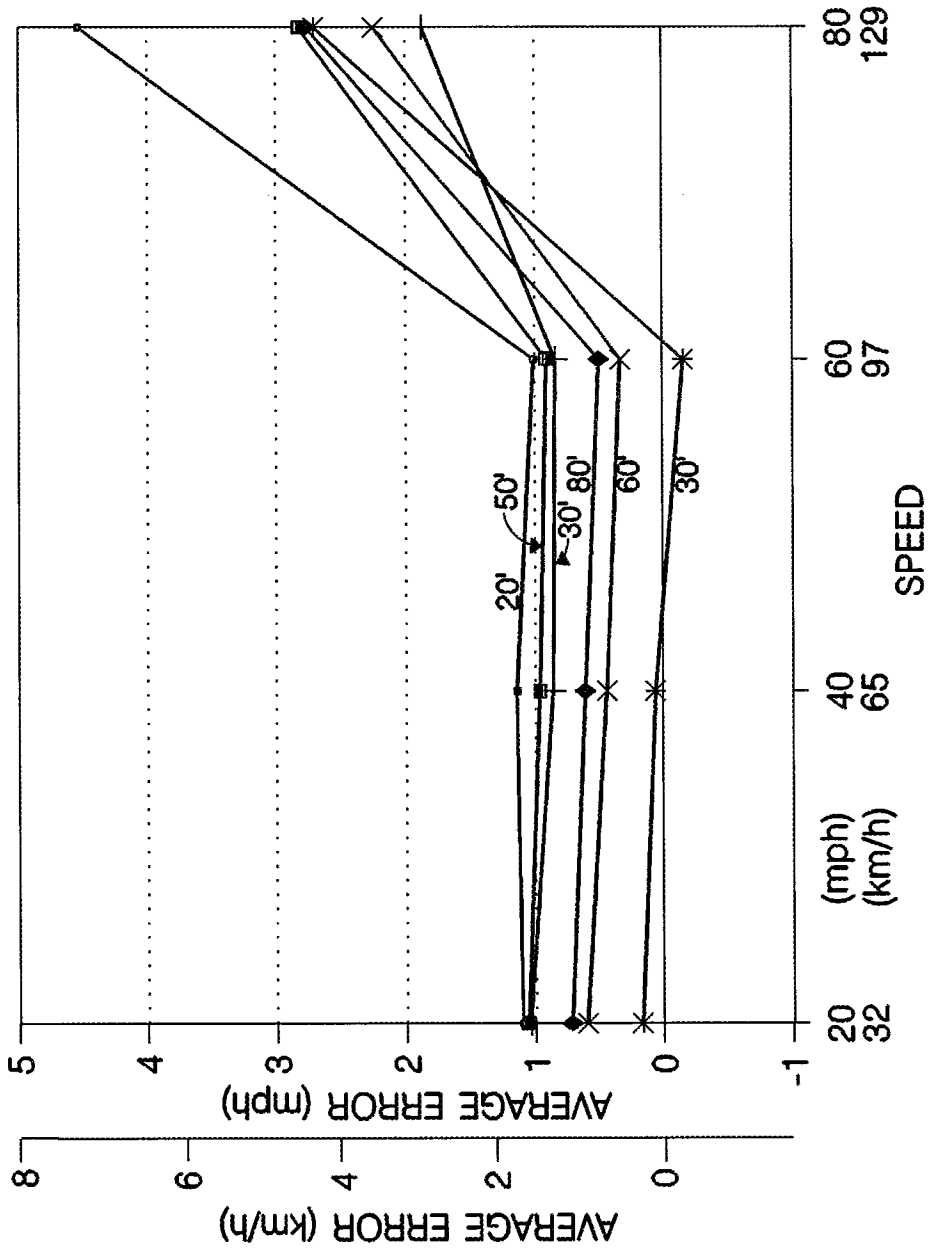

Figure 8. Average Error for Different Speed Trap Lengths for a Large Car and Identical Detector Order

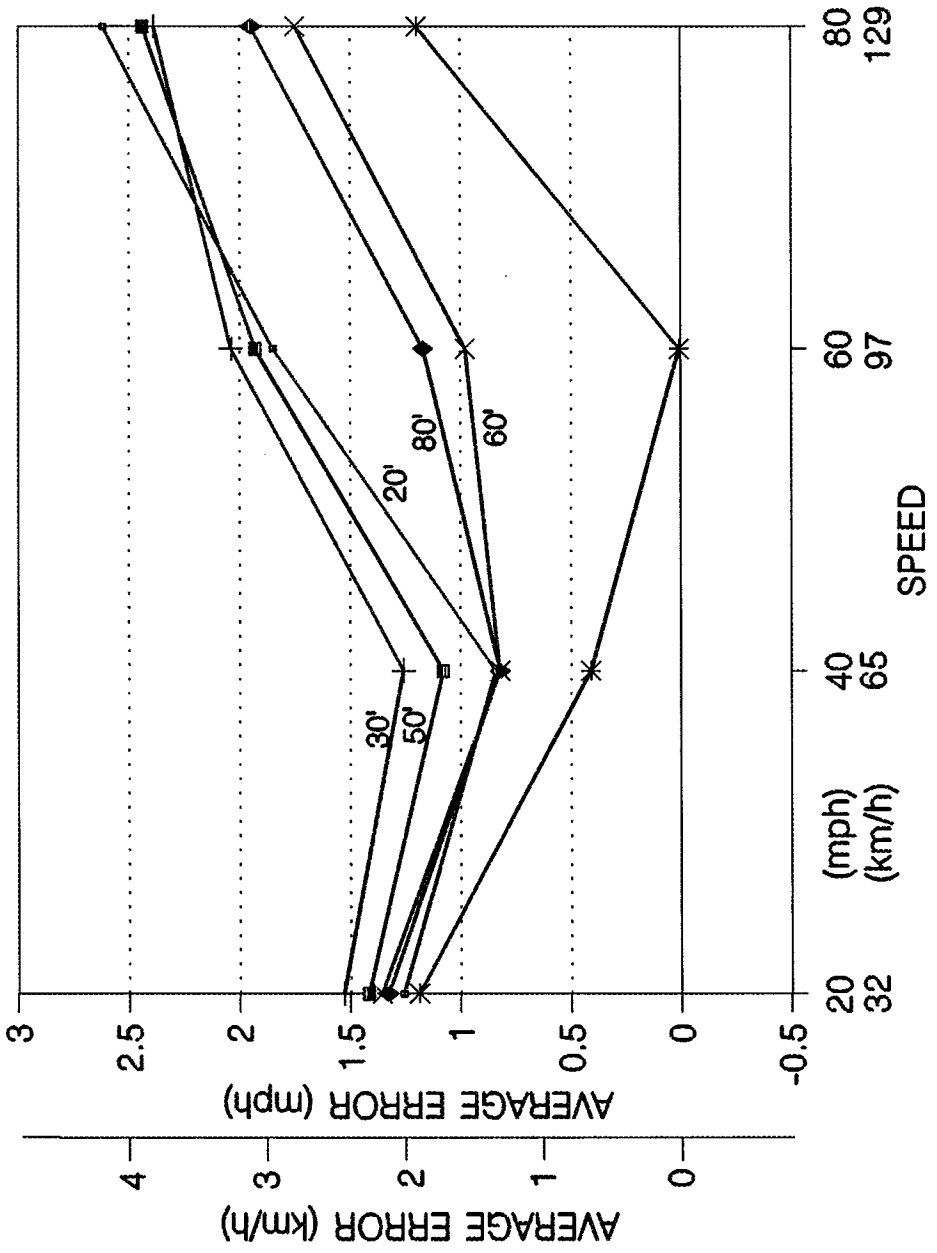

Figure 9. Average Error for Different Speed Trap Lengths for a Pickup Truck and Identical Detector Order

5.0 WIRE TYPE STUDY RESULTS

Various types of electrical wires can be used to construct inductance loops. However, it must be recognized that different wire types and construction methods can create different magnetic fields and thus, affect the accuracy and consistency of inductance loop operation. This part of the study deals with wire types and construction methods as they affect the accuracy and consistency of speed measurements. The results are presented according to speed trap wire type, and then a statistical comparison of the three speed trap types is presented. The best wire type to be used with inductance loop detectors for speed measurement accuracy is identified in this portion of the study.

To test the effects of wire type on accuracy and consistency, speed measurements were made using three different loop combinations: 1) two loops formed using single conductor wire; 2) one single conductor loop and one multi-conductor cable loop; and 3) two loops formed using multi-conductor cable. All loops were spaced 9 meters apart, and all loops consisted of three turns of wire.

Infra-red light sensors were placed in line with the leading edge of each loop so that an accurate passage time could be measured for comparison with passage time measured by the loop detector speed traps.

5.1 SINGLE CONDUCTOR WIRE LOOP SPEED TRAP

In the trap composed of two single conductor loops, the mean speed difference was -6.770 km/h (-4.231 mph). A negative value simply means that the speed measured by the loop trap was less than the speed measured by the light sensor trap. The standard deviation was 1.068 km/h (0.663 mph). This means that speed differences of 9 km/h (5.5 mph) could be expected more than 5% of the time. Further, a speed difference of 6.77 km/h (4.23 mph) at a speed of 64 km/h (40 mph) would result in a 10 % error. For freeway traffic management, this error is most likely unacceptable.

5.2 SINGLE- AND MULTI-CONDUCTOR WIRE LOOP COMBINATIONS

Tests using loops C and D to form a speed trap resulted in a mean speed difference of -0.787 km/h (-0.489 mph), and a standard deviation of 1.097 km/h (0.682 mph). This shows a substantial improvement over the speed trap using two single conductor wire loops. The relatively large standard deviation indicates some inconsistency in readings.

5.3 MULTI-CONDUCTOR WIRE SPEED TRAP

Tests using a speed trap formed by identical multi-conductor wire loops provided the best results in measuring speed differences. The mean difference was 0.224 km/h (0.139 mph) with a standard deviation of 0.828 km/h (0.514 mph). The multi-conductor wire speed trap was, by far, the most accurate in measuring the speed of a large car at 64 km/h (40 mph). With less than a 1 percent difference in the expected speed and the measured speed, the multi-conductor cable is very attractive for use in speed traps.

Several constraints associated with using multi-conductor wire inductance loops should be noted. First, a wider saw cut in the pavement is required to accept the cable. Multi-conductor cable requires an 8 mm (5/16 inch) saw cut, while single conductor wire requires a 6.4 mm (1/4 inch) saw cut. This will require a larger saw blade at a higher cost, and more loop sealant. On the other hand, placing one cable in a saw cut takes less time than placing individual wires into a saw cut. In addition, there is the problem of placing the individual conductor in close proximity to other loops in the slot so as to ensure a uniform electromagnetic field. The placement time saved by using multi-conductor cable should result in money saved from reduced construction cost and reduced delay to the driver during construction, and improved loop performance. During construction, lanes will be closed, thereby delaying the driver. The shorter the time needed to place the loops, the less delay to the driver. Even though the diamond saw blade will be more expensive, the benefits should outweigh the problems associated with using multi-conductor wire.

5.4 STATISTICAL ANALYSIS

In order to determine that the speed traps were, in fact, statistically different, a statistical test on two independent samples was performed. The t-test statistic was used with a null hypothesis that the mean speed difference measured from speed trap number one was equivalent to the mean speed difference measured from speed trap number three. Speed trap number two was then compared to speed trap number three to show that it is indeed necessary that speed traps be constructed with identical inductance loops to provide the best results. The table t-value was determined by using an alpha value of 0.05 and 40 degrees of freedom (11). The results of the statistical test are shown in Table 4.

Table 4. Statistical Comparison of Different Wire Types

Statistical Test	Table t-value	Calculated t-value	Result
Speed Trap 1 vs. 3	1.684	22.78	Reject Ho
Speed Trap 2 vs. 3	-1.684	-3.235	Reject Ho

Both statistical tests lead to the rejection of the null hypothesis. Therefore, the mean speed difference measured by speed trap number 3 (2 multi-conductor loops) was in fact different from the mean speed difference measured by speed traps number 1 and 2 (both utilizing single conductor wire loops).

5.5 SUMMARY

Speed traps constructed of multi-conductor cable do, in fact, operate better than speed traps constructed of single conductor wire. With multi-conductor cable loop traps, less than one percent error is expected in speed measurement at 64 km/h (40 mph) with a large car. The results also show that identically constructed multi-conductor speed traps operate more accurately than do speed traps using non-identical inductance loops. For accurate speed measurement on the freeway, it is recommended that the inductance loops be constructed of multi-conductor wire. For use where speed is not measured, single conductor wire may be sufficient, but the reduced construction time may justify the use of multi-conductor cable.

6.0 RESPONSE TIME STUDY RESULTS

Response time of an inductance loop detector is the time interval beginning when a vehicle crosses the leading edge of the loop, and ending when the vehicle is actually detected. Response time varies, dependent upon vehicle size, vehicle weight, vehicle ground clearance, the sensitivity setting in the detector and the wire type used in the loop. This portion of the study was conducted to analyze the effects of vehicle type, detector type (make), detector sensitivity setting, and wire type on response time.

Response time was measured by measuring the time difference between a detection by the inductance loop detector circuit and the passage of a vehicle over the leading edge of the loop as measured by the infrared light sensors. Light sensors were placed directly over the leading edge of each loop.

6.1 LARGE CAR TESTS

6.1.1 Detector Systems Detector

The response time measured by the Detector Systems individual detector for the large car ranged from 0.15 seconds to 0.048 seconds, depending on the sensitivity setting. The lower sensitivity had a longer response time. This is expected because the threshold inductance charge at low sensitivity is much higher than that at the higher sensitivities and will therefore cause a vehicle to be detected later. Figure 10 illustrates the response time for each of the Detector Systems detectors in a 9 meter (30 foot) multi-conductor cable inductance loop speed trap when the large car was traveling at 32 km/h (20 mph). The response time also tended to decrease with speed until a certain level was reached. The response time at 97 km/h (60 mph) and low sensitivity was approximately 0.09 seconds. The results of response time vs speed and sensitivity are presented in Figures C-1, C-2, and C-3 in Appendix C. In general, increases in speed reduced response time, as did increasing the sensitivity setting. Response time appeared to level off at 0.05 sec for higher speeds and higher sensitivity settings.

6.1.2 Naztec Detector

The Naztec card rack detector generally measured shorter response times than did the Detector Systems detectors. At low sensitivity for 32 km/h (20 mph) the lag time was on average only 0.025 seconds. The Naztec detector did, however, register negative response times. This phenomenon occurs when a vehicle is detected before reaching the leading edge of the inductance loop. This can occur when the magnetic field created by the detector extends over the plane of

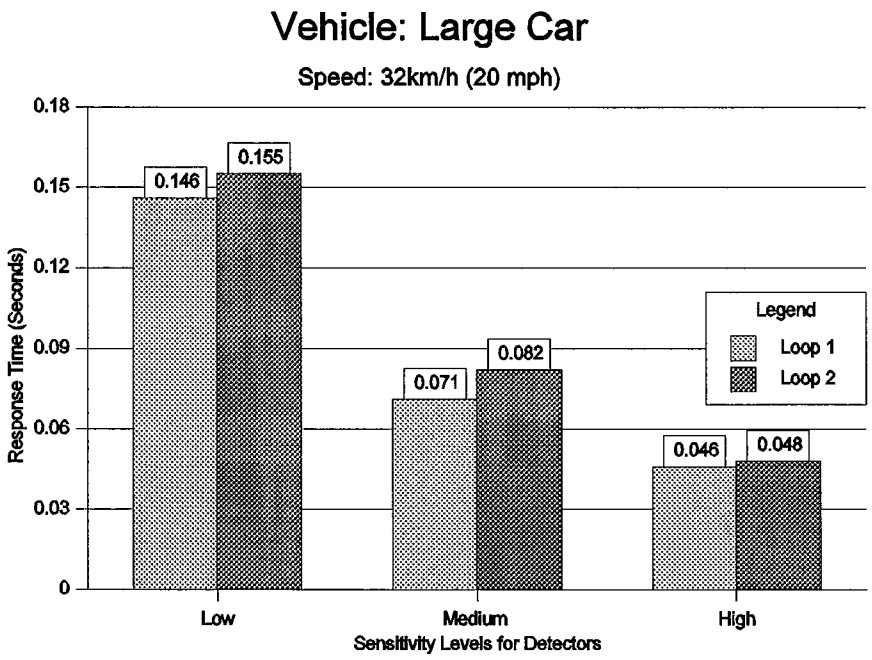

Figure 10. Response Times for Detector Systems Detector (Large Car)

the loop. The response time becomes more negative as the sensitivity is increased on the Naztec detector. The response time does not extend beyond a -0.05 seconds. Figures C-4, C-5, C-6, and C-7 in Appendix C present the results of the large car studies with the Naztec detector.

6.2 SMALL CAR TESTS

6.2.1 Detector Systems Detector

The small car had shorter response times than did the large vehicle. The response time at low sensitivity for 32 km/h (20 mph) was only 0.08 seconds. The response time at high sensitivity was between 0 and 0.022 seconds for the two loops. The response time also decreased with increased speed and increased sensitivity. At 97 km/h (60 mph) the response time reached -0.005 seconds for one of the loops. The other loop leveled off at 0.021 seconds. Figures C-8, C-9, and C-10 in Appendix C present the results of the response time studies for the small car with the Detector Systems detector. The small car, due to its operating characteristics and the runway length, was unable to reach 129 km/h (80 mph) for this study.

6.2.2 Naztec Detector

The response time measured with the Naztec detector was again shorter than with the Detector Systems detector. The response time at low sensitivity and 32 km/h (20 mph) was on average 0.05 seconds. The response time also fluctuated between positive and negative values. The medium sensitivity cases measured the most negative response times. Figure C-4 in Appendix C presents the results of the tests using the Naztec detector and the small car. Response times for speeds of 97 km/h (60 mph) and 129 km/h (80 mph) were not measured.

6.3 PICKUP TRUCK TESTS

6.3.1 Detector Systems Detector

The tests with the pickup truck also showed decreasing response times with increasing sensitivity and increasing speed. The response time at low sensitivity was 0.11 seconds for the 32 km/h (20 mph) case. The response time was 0.030 seconds at high sensitivity for the 32 km/h (20 mph) case. The response time did, however, tend to level off at 0.05 seconds for the higher speed studies. Figure C-5 in Appendix C presents the results of the response time studies for the pickup truck and the Detector Systems detector. Once again, tests were not conducted at 129 km/h (80 mph) due to the limited amount of runway length and the vehicle operating characteristics.

6.3.2 Naztec Detector

The Naztec detector measured positive response times at low sensitivity and negative response time at medium and high sensitivity for the 32 km/h (20 mph) tests. The response times were generally shorter than those measured by the Detector Systems detector. Unlike other test cases, the Naztec detector measured negative lag times for all sensitivity levels at speeds of 64 km/h (40 mph) and 97 km/h (60 mph). This indicates a stronger magnetic field created by the Naztec detector. The 97 km/h (60 mph) case had the shortest lag times. This is consistent with the previous studies with the Naztec detector, and illustrates the random nature of inductance loop response time. Figures C-6 in Appendix C presents the results of this portion of the study. Tests were not conducted at 129 km/h (80 mph).

6.4 MOTORCYCLE TESTS

6.4.1 Detector Systems Detector

Response times for the motorcycle were only measured at medium and high sensitivity and at 32 km/h (20 mph) and 64 km/h (40 mph) for both detectors in this study. The response time decreased with increasing sensitivity. The effect of speed on the response time was relatively non-

existent. A negative response time was measured on one of the loops at high sensitivity. Figure C-7 in Appendix C presents the results of this study.

6.4.2 Naztec Detector

The response time also decreased with speed and sensitivity for this case. The Naztec detector continued to measure negative lag times for the higher sensitivity cases. No distinct trend was noticeable in the data. Figures C-8 in Appendix C presents the results of the motorcycle study with the Naztec detector.

6.5 HIGH PROFILE TRUCK TESTS

6.5.1 Detector Systems Detector

The response time to detection of the high profile truck decreased with increasing sensitivity for one of the loops and increased with the other. Tests were only conducted at 32 km/h (20 mph) due to the operating characteristics of the high profile truck. The odd size of the high profile truck led to various points of detection and affected the response time measurement. Figure C-7 in Appendix C presents the results of this case.

6.5.2 Naztec Detector

The response time for detection of the high profile truck using the Naztec detector followed previous trends. The response time was positive at low sensitivity and negative at medium and high sensitivity settings. The lag time was only 0.05 seconds for the 32 km/h (20 mph) low sensitivity case. Figure C-8 in Appendix C presents the results of this case.

6.6 INDUCTANCE LOOP WIRE TYPE

Multi-conductor cable inductance loops tended to have shorter response times than did single conductor wire loops for both the large car and the pickup truck using the Detector Systems detector. Single conductor wire inductance loops measured response times at 64 km/h (40 mph) and low sensitivity to be 0.09 seconds for the large car. On the other hand, the response time measured by the multi-conductor loop was only 0.05 seconds. Figure 11 illustrates the response time for each detector for the various wire types, the large car, and 64 km/h (40 mph). The response time also decreased with speed. The response time for the single conductor wire loops leveled off at 0.06 seconds, while multi-conductor cable wire loop response time leveled off at approximately 0.01 second. Figures C-9 and C-10 in Appendix C indicate that the response time is dependent on the inductance loop wire type, and the vehicle crossing the loop.

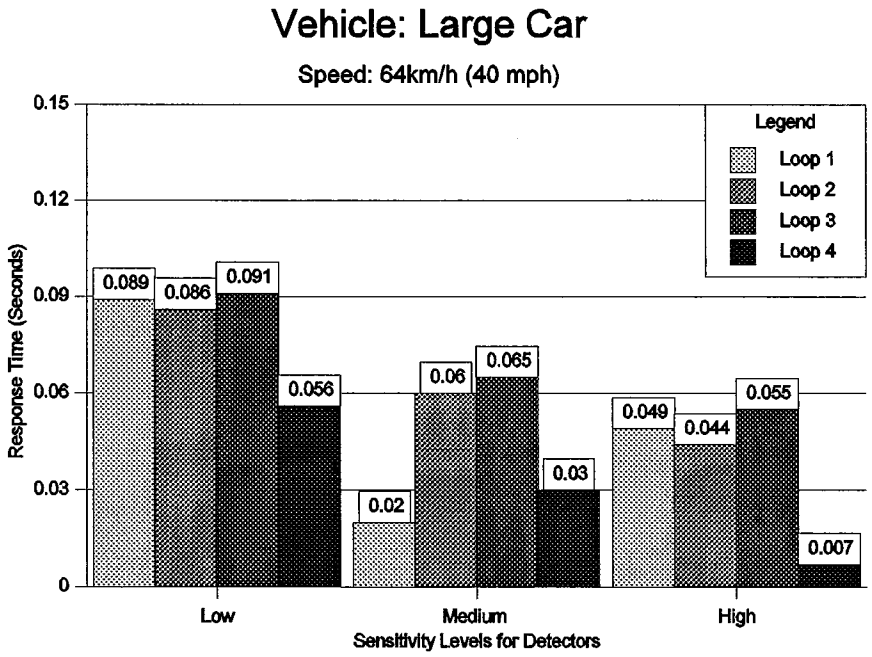

Figure 11. Response Times for Detector Systems Detectors Single Strand Loops (Loops 1, 2, 3) and Multiconductor Cable (Loop 4) (Large Car)

6.7 SUMMARY

The response time relative to when a vehicle crosses the leading edge of an inductance loop is affected by the vehicle size, vehicle speed, detector type, detector sensitivity, and inductance loop wire type. The response time decreased with smaller sized vehicles. Smaller vehicles tend to change the electromagnetic field created by the inductance loop earlier due to the vehicle's lower ground clearance and shorter distance to the engine block and front axle. Faster speeds tended to reduce the response time. This was expected because a vehicle traveling at a faster speed will take a shorter time to reach the same point in the loop that sets off a detection as would a slower moving vehicle. Different detectors also measured different response times. Negative and positive response times were measured by the Naztec detector, demonstrating that the Naztec detector places a stronger electromagnetic field on the inductance loop than does the Detector Systems detector. Higher sensitivity settings resulted in shorter response times for the Detector Systems detector, but when negative response times were measured by the Naztec detector, longer response times were measured. Finally, the inductance loop wire type affects the response time. Multi-conductor cable loops measure shorter response times than do single conductor wire

inductance loops. The multi-conductor cable provides a more uniform, stronger electromagnetic field than identical loops constructed using single conductor wire, causing a shorter response time.

7.0 SPEED MEASUREMENT ACCURACY STUDY RESULTS

To determine the accuracy of speed measurements using loop detectors, 10 test vehicle runs were made across a speed trap formed by two loops at four speeds ranging from 32 to 129 km/h (20 to 80 mph). The loops were Loops E and F at the Riverside Campus test site, which are the two multi-conductor loops spaced at 9 meters. Five types of test vehicles were used: large car, small car, pickup truck, high-profile truck, and a motorcycle. Two types of detectors were used: Detector Systems Model #813-1103SS, and Naztec Card Rack system < Model 722-Tx/I. The detectors were set at medium-high frequency throughout the tests, and the sensitivity was varied: low, medium and high.

Speed measurement accuracy was determined by computing and comparing speeds measured concurrently by two methods: time measurement for vehicle passage across the loop trap, and time measurement for vehicle passage across a trap formed by infra-red sensors installed at the leading edge of each of the loops. Speeds were computed using the measured times and the trap length, and compared on the basis of speed differences for the two measurement methods. The standard deviations of the speed differences were computed as a measure of consistency in speed measurements.

In analyzing the results of these tests, it is assumed that speeds measured using the infra-red devices are accurate, and the speeds measured by the loop trap are subject to error resulting from variations in detector response time. The researchers felt that it is important for practitioners to be cognizant of the existence of error in speed measurements and its expected range and magnitude. Further, they should be aware of the standard deviation as a measure of the variability that they may expect in detector applications. Certainly, the speed differences may be accounted for through routine in-field calibration using a test vehicle travelling at a known speed. However, a large standard deviation indicates variability in measuring passage time of subsequent vehicles, and is indicative of variation that cannot be accounted for by in-field calibration. For a given installation, its variability could be determined through recording and analyzing speeds measured through repeated passes of the in-field calibration vehicle.

The results of the speed difference tests are illustrated in Figures 12 to 29. Complete results are presented in Figures C-1 to C10 in Appendix C. The results have been studied in various sub-comparisons, and it was decided to provide a visual comparison of speed differences and standard deviations for the two detector types. Figures 12 through 19 permit a comparison of speed differences for four of the five test vehicles as measured using Detector Systems detectors. It is noted that speed differences were as large as 6 km/h (3.5 mph) but normally a maximum of about 4 km/h (2.5 mph) for three of the most commonly observed vehicles - large cars small cars, and pickups. This amounts to errors as large as 6% but normally 3 to 5% or less. Errors for motorcycles were as high as 12%.

It is noted that as speed increases, variability increases, as shown in the plots of standard deviation. Also, high sensitivity settings produce higher standard deviations, and thus higher variability.

Figures 20 through 27 provide a comparison of speed differences for four of the test vehicles using the Naztec Card Rack system detectors. The speed differences for the large car are greatly different from the differences using the other vehicles, and there are no known explanations. This appears to be an "outlier" variation, where the difference in speed measurement was as great as 12 km/h (7.45 mph) which is a 10 to 12% error. It should be noted, however, that the standard deviation for the large car was generally about 1.5 km/h (1 mph). For the small car and the pickup truck, the speed differences were very small, usually less than 1 km/h (0.5 mph). Also, the standard deviation was less than about 1.25 km/h (3/4 mph).

Speed differences for the motorcycle were as high as 9%, but the standard deviation was about 1 km/h (0.5 mph). It should be noted that the motorcycle was not detected for speeds of 97 km/h (60 mph) or when detectors were set for low sensitivity. This was true for Detector Systems, also.

These results are interpreted to mean that both detectors produce results that are reasonably reliable. Errors in measuring speeds of commonly occurring vehicles in the range of 32 to 97 km/h (20 to 60 mph) normally will be within 5 to 6% and more commonly 3 to 5% of actual speeds for both detectors. However, the Naztec Card Rack system seems to have the edge on repeatability. The standard deviation for Detector Systems detectors of 2.5 to 4 km/h (1.5 to 2.5 mph) means that measured speeds of successive vehicles may vary 6 to 16 km/h (10 mph) or more in 5% of the observations. For the Naztec systems, with a range in standard deviations of 1.0 to 2.6 km/h (0.6 to 1.6 mph), the error could be 4 to 8 km/h (2.5 to 5 mph) or more in 5% of the observations.

For the application standpoint, it appears that the Naztec Card Rack system has an advantage because of the smaller standard deviation. An in-field calibration procedure can correct the error in speed measurement provided that there is consistency in loop performance.

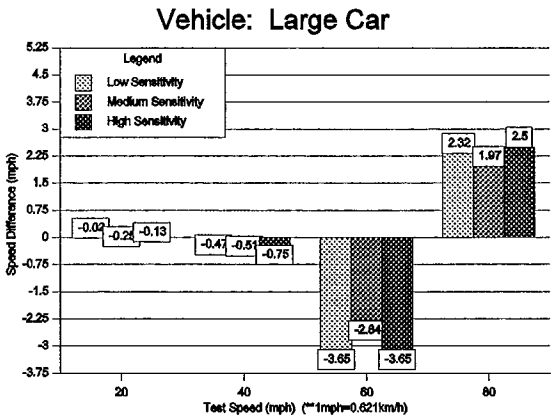

Figure 12. Speed Difference for 9 meter (30 foot) Trap (Detector Systems, Large Car)

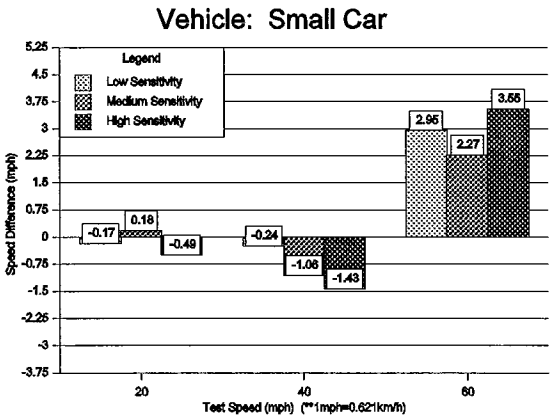

Figure 14. Speed Difference for 9 meter (30 foot) Trap (Detector Systems, Small Car)

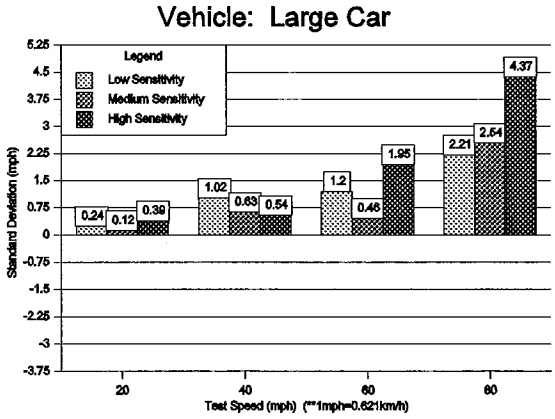

Figure 13. Standard Deviation of the Speed Difference (Detector Systems, Large Car)

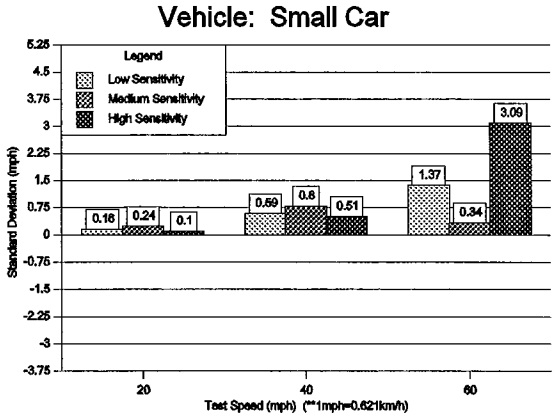

Figure 15. Standard Deviation of the Speed Difference (Detector Systems, Small Car)

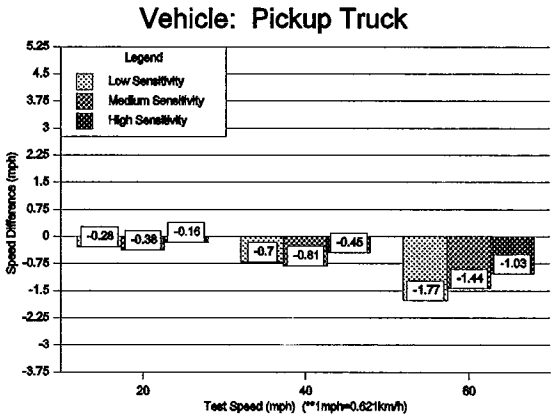

Figure 16. Speed Difference for 9 meter (30 foot) Trap (Detector Systems, Pickup Truck)

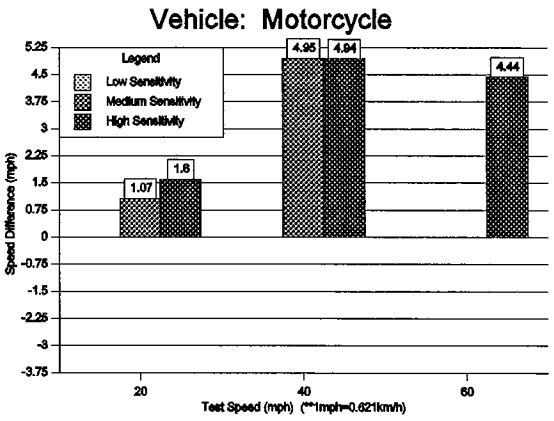

Figure 18. Speed Difference for 9 meter (30 foot) Trap (Detector Systems, Motorcycle)
[Note: Motorcycle was not detected at low sensitivity at any speed, or at medium sensitivity at 60 mph]

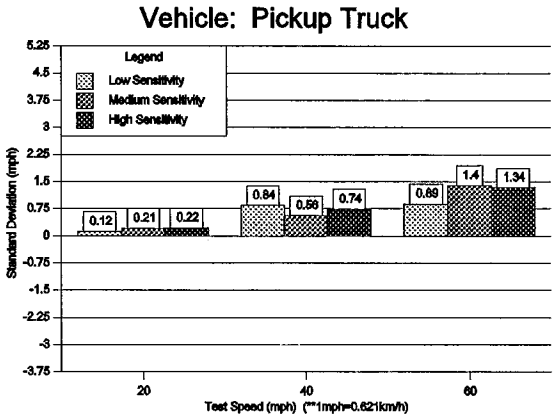

Figure 17. Standard Deviation of the Speed Difference (Detector Systems, Pickup Truck)

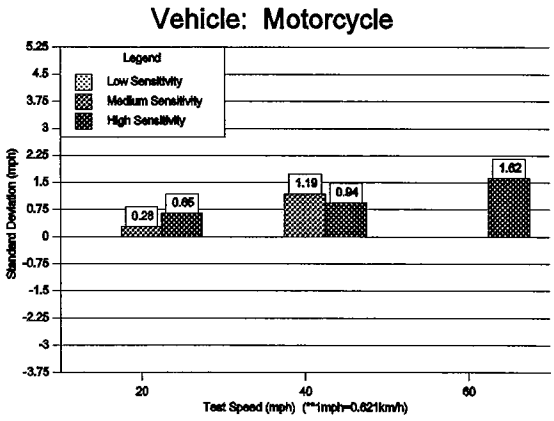

Figure 19. Standard Deviation of the Speed Difference (Detector Systems, Motorcycle)
[Note: Motorcycle was not detected at low sensitivity at any speed, or at medium sensitivity at 60 mph.]

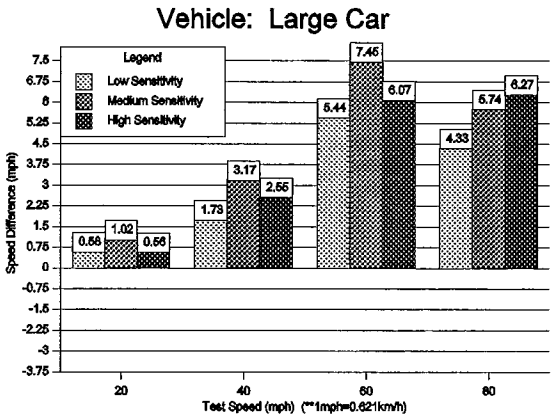

Figure 20. Speed Difference for 9 meter (30 foot) Trap (Naztec, Large Car)

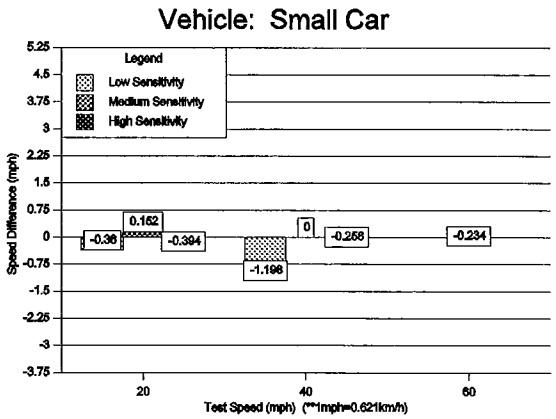

Figure 22. Speed Difference for 9 meter (30 foot) Trap (Naztec, Small Car)

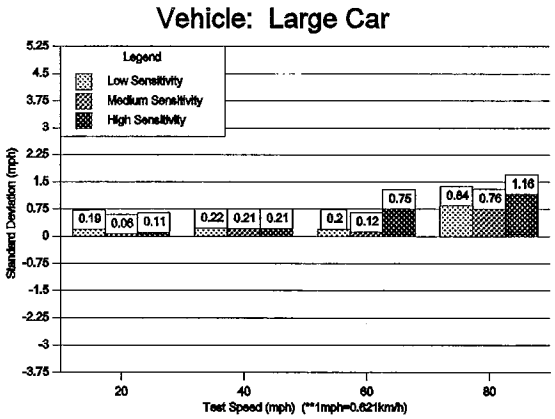

Figure 21. Standard Deviation of the Speed Difference (Naztec, Large Car)

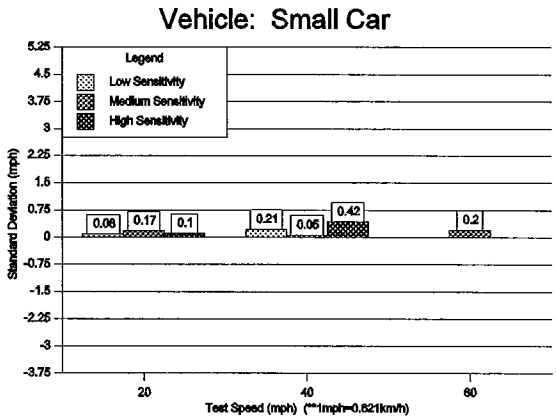

Figure 23. Standard Deviation of the Speed Difference (Naztec, Small Car)

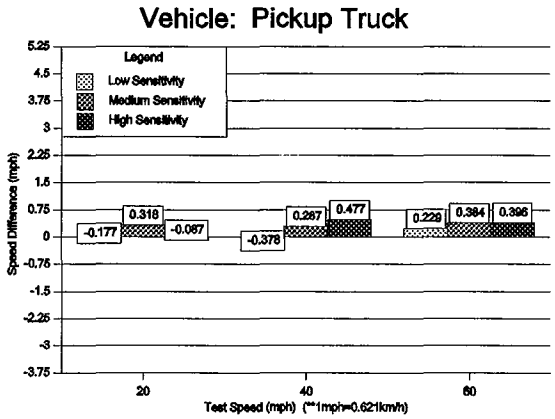

Figure 24. Speed Difference for 9 meter (30 foot) Trap (Naztec, Pickup Truck)

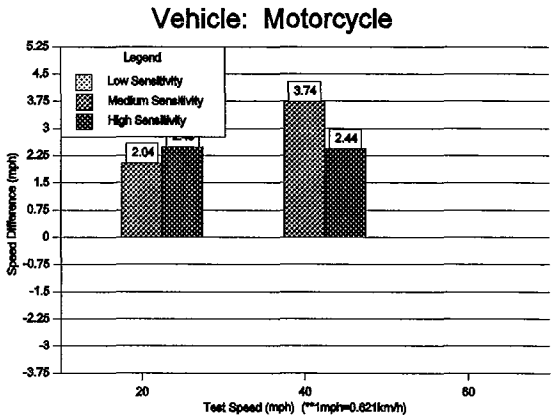

Figure 26. Speed Difference for 9 meter (30 foot) Trap (Naztec, Motorcycle)

[Note: Motorcycle was not detected at low sensitivity at any speed, or at 60 mph]

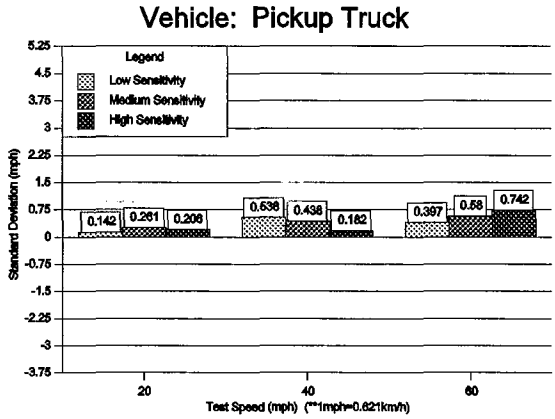

Figure 25. Standard Deviation of the Speed Difference (Naztec, Pickup Truck)

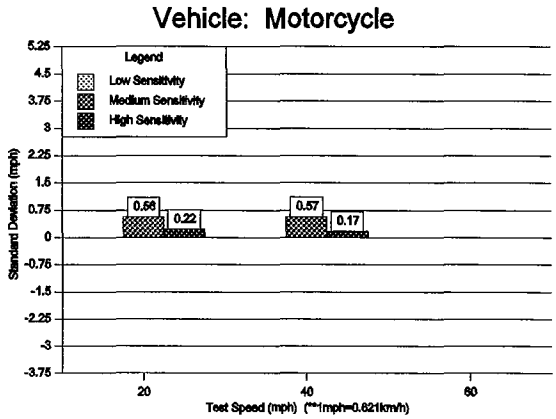

Figure 27. Standard Deviation of the Speed Difference (Naztec, Motorcycle)

[Note: Motorcycle was not detected at low sensitivity at any speed, or at 60 mph.]

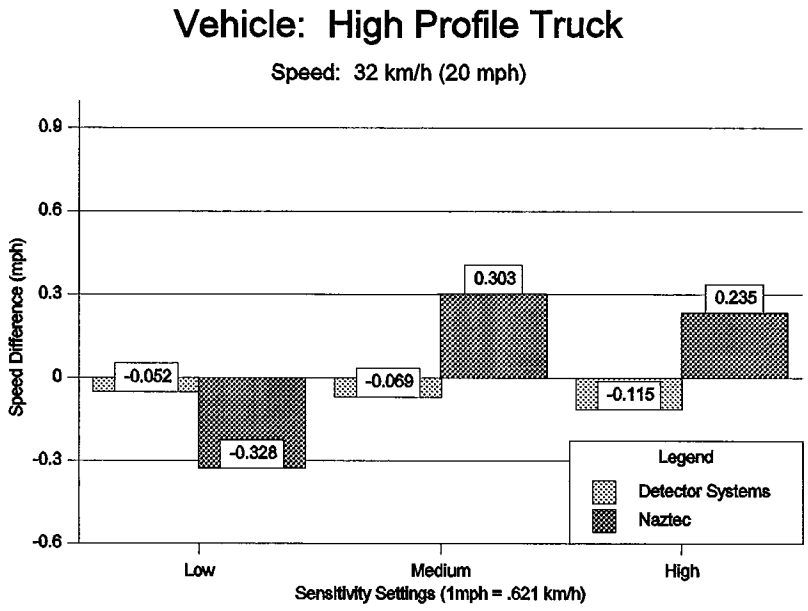

Figure 28. Speed Difference for 9 meter (30 foot) Trap (High Profile Truck)

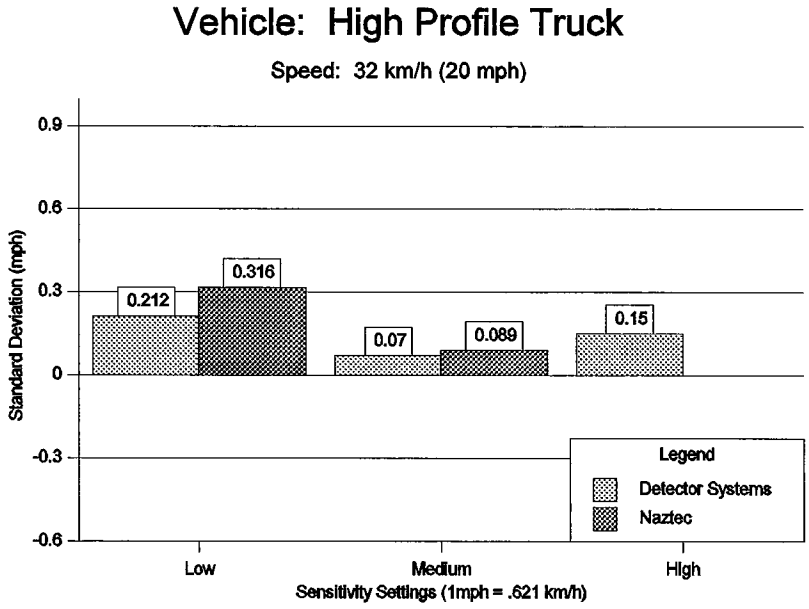

Figure 29. Standard Deviation of the Speed Difference (High Profile Truck)

8.0 CONCLUSIONS AND RECOMMENDATIONS

This study has yielded information that will be extremely beneficial to the transportation profession in this rapidly developing era of traffic management strategies. For traffic management to be effective, the management staff must have timely, accurate and factual data as a basis for making decisions. Fundamental data requirements are traffic volumes and traffic speeds.

Both of these measures can be accomplished using induction loop detector systems, provided they can provide sufficient accuracy. The purpose of this study was to evaluate loop detector characteristics as they affect accuracy and reliability of traffic measurements. Of particular concern is the accuracy and reliability in measuring traffic speeds. Characteristics of particular concern were as follows:

1. Optimal speed trap length.
2. Loop wire type/loop construction.
3. Detector response time.
4. Speed measurement accuracy.

8.1 OPTIMAL SPACING OF SPEED TRAPS

This study demonstrated that speed measurements were reasonably accurate at trap lengths of 6 to 24 meters. Previous research had shown that crosstalk can occur between two identical detectors operating on the same frequency and sensitivity setting when spaced at 6 meters. And, this study showed that it is essential that two detectors used in speed measurement be identical. Therefore, the 6 meter spacing of loops should be ruled out.

As loop spacing in traps increases, there is an increased probability that vehicles will begin a lane change in the trap length and thus miss one of the detectors, providing an erroneous speed value. Considering the lane changing and crosstalk constraints, the "optimal" speed trap is 9 meters. Certainly, longer traps may be used successfully, but the engineer should be cognizant of the higher probability of errant data due to lane changes as the trap length increases.

8.2 INDUCTANCE LOOP WIRE TYPE

This study has shown conclusively that the type of wire and the manner in which a loop is formed strongly influences the accuracy and reliability of detection and speed measurement. Loops formed using single conductor were not nearly as dependable as those formed using multi-conductor cable. The principal attribute of the multi-conductor cable was the outer sheath that held all conductors in uniform proximity, and thus maintained a more uniform electromagnetic

field. The multi-conductor cable may require a slightly wider saw cut, but its ease of installation and accurate performance should justify its use.

There were two types of cable used in this study. Loop D was constructed using a cable of 6 #18 AWG conductors twisted in pairs. Loops D and E were constructed using 4 #12 AWG conductors in a cable. The conductors in both cables were twisted and enclosed in an outer plastic sheath. This resulted in a round cable, about 5/16 inches in diameter. It is believed that a flat cable or web wire will provide sufficient control of wire placement so that the electromagnetic field is controlled. Therefore, it is recommended that designers pursue the availability of a flat wire cable that would be sufficiently narrow to be placed in a 1/4 inch slot and formed in such a manner that the spacing of successive turns are uniformly spaced with other turns forming the loop.

8.3 DETECTOR RESPONSE TIME

The measure of time from when a vehicle crosses the leading edge of the loop until it is detected is the response time of the detector. Response times can be positive or negative. A positive response time means detection occurred after the vehicle passes the leading edge of the loop, and a negative response time means that the vehicle was detected prior to passing over the edge of the loop. This study showed that response time was affected by vehicle size, vehicle speed, vehicle type, loop wire type, detector type and sensitivity setting.

Response time decreased with vehicle size. Smaller vehicles tend to change the electromagnetic field of the loop earlier because the vehicle is lower to the pavement, and there is a shorter distance from the bumper to the engine and front suspension. Faster speeds result in shorter response time. Generally, the "response distance" is the same so a higher speed would result in a shorter travel time for the given distance. In other words, a vehicle travelling at a faster speed will take a shorter time to reach the same point in the loop.

Different detectors have different response times. Detector Systems detectors response times were almost always positive, while Naztec detectors were mostly all negative response times. Apparently, the Naztec detector places a stronger electromagnetic field on the loop. Using higher sensitivity settings resulted in shorter response times for the Detector Systems detector because the response time was positive. Because the Naztec detector produced negative response times, higher sensitivity settings increased the negative values.

Response times using multi-conductor cable are significantly shorter and more uniform than response times using loops formed with single conductor wire. This is attributed to the uniformity of the electromagnetic field created by the multi-conductor loop.

The more common vehicles, autos and pickup trucks, were consistent in response times. Motorcycles and high profile trucks will cause difficulties in detection when loops are used for volume and speed measurement. Fortunately, these vehicles do not constitute a large proportion of the traffic stream when measurement accuracy is critical.

8.4 SPEED MEASUREMENT ACCURACY

The accuracy of speed measurement depends on a number of things, several of which have been included in this study. First, it is essential that loops be identical, using multi-conductor cable. Second, identical detectors must be used, and they must be operating on the same frequency and identical sensitivity settings. Of the detectors used in this study, it is recommended that the card rack system be used. Apparently, it is easier to achieve identical detector operation when the detectors are feeding off the same power source, and utilize a coordinated loop scanning arrangement. This finding is not to be construed as a brand endorsement but an appraisal of a manufacturing technique. Perhaps there are other card rack systems that are equally or more accurate than the systems tested. There are systems that operate four or more detector units from one card.

Thirdly, it is essential that some form of calibration be used routinely with speed measurement using loop detection. Operating conditions for detectors appear to be transient, depending on various environmental, climatic and traffic operating factors. To obtain consistent results, it is important to begin with equipment and methods that produce the most consistent results and then calibrate the system frequently.

9.0 REFERENCES

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10.0 APPENDIX A
DIMENSIONS OF ODD SIZED VEHICLES

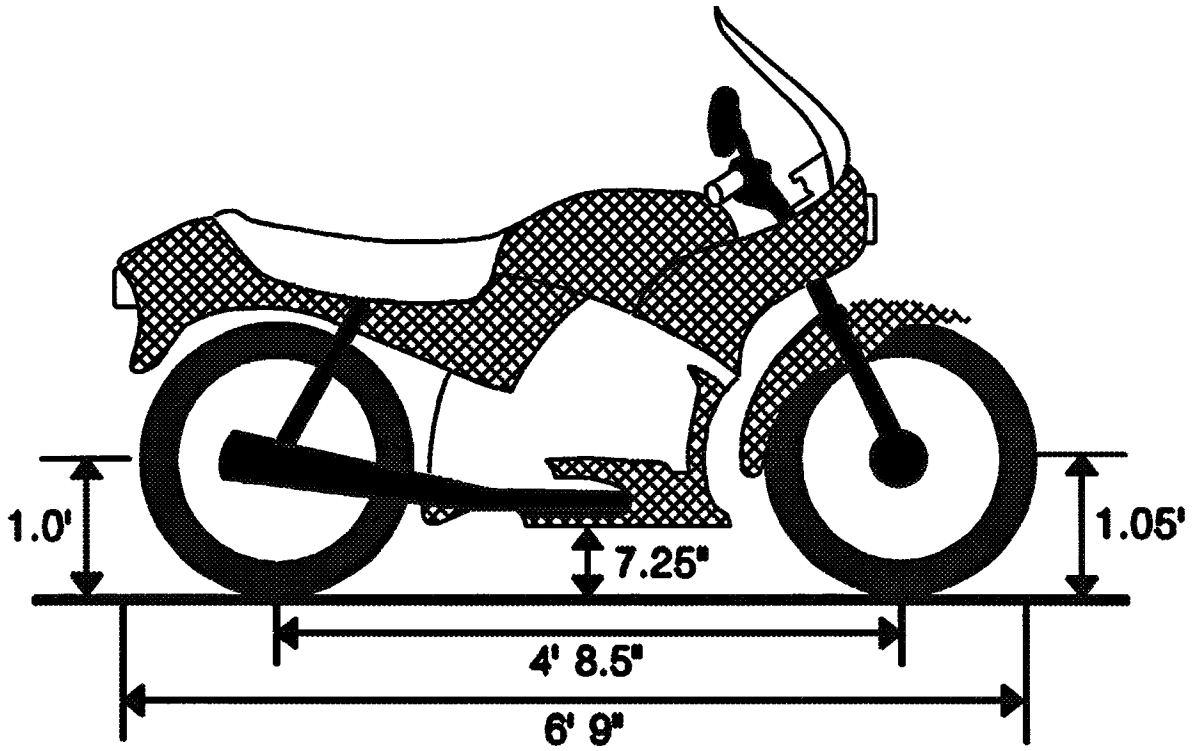


Figure A-1. Dimensions of the 1982 Suzuki 3006SL Motorcycle
Note: 1 inch = 2.54 centimeters and 1 foot = .3048 meters

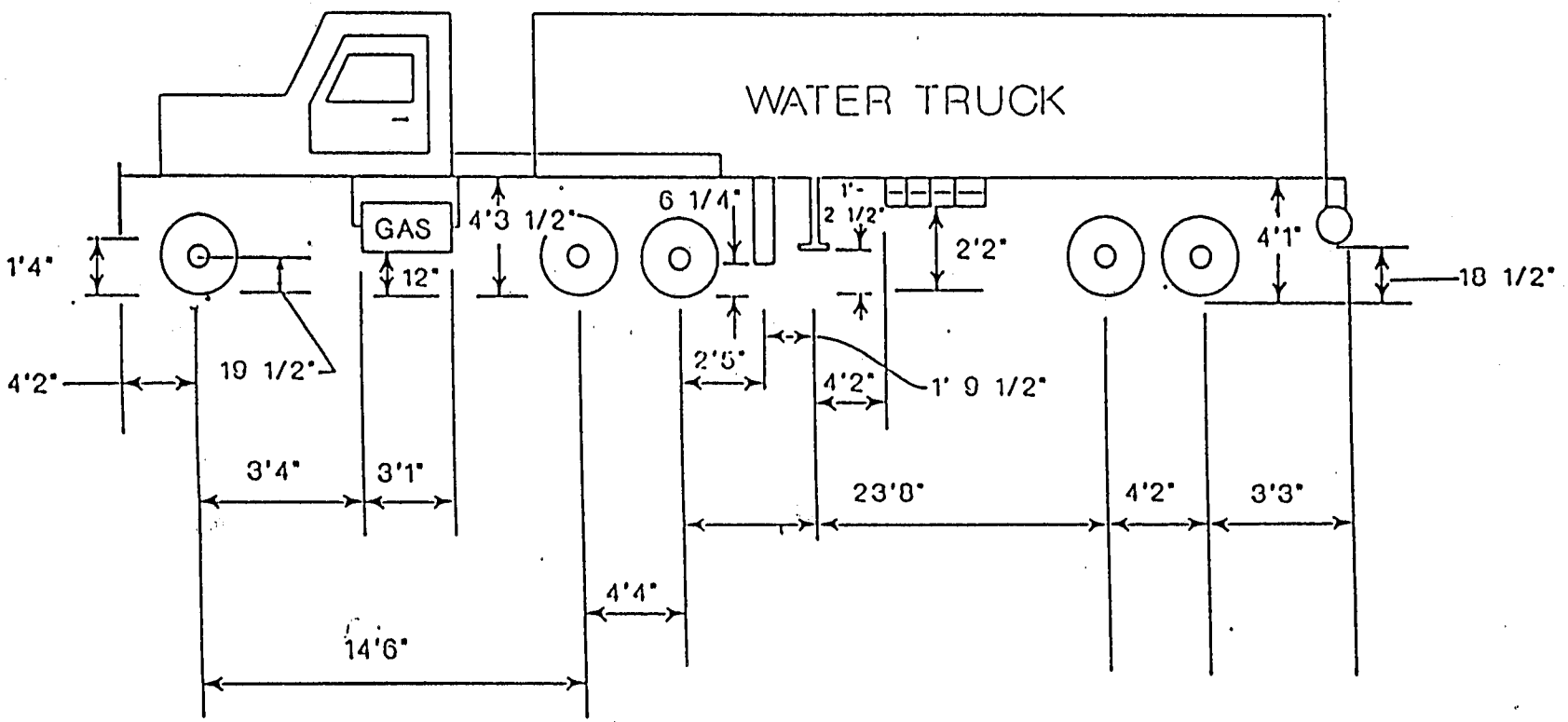


Figure A-2. Dimensions of the Kenworth Tractor-Trailer Combination

Note: 1 inch = 2.54 centimeters and 1 foot = .3048 meters

11.0 APPENDIX B

AVERAGE ERRORS FOR VARYING SPEED TRAP DESIGNS

Table B-1. Comparison of Average Error and Standard Deviation for Different Detector Orders for a Large Car

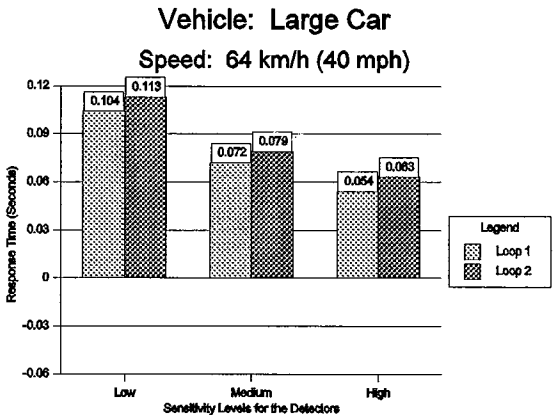
Speed and Trap Distance	Detector Order A,B,C,D		Detector Order C,D,B,A		Detector Order A,A,A,A	
	Average Error (mph)	Standard Deviation	Average Error (mph)	Standard Deviation	Average Error (mph)	Standard Deviation
20 mph						
20'	8.84	1.46	-1.12	1.01	1.10	0.69
30'	1.56	1.37	3.02	1.35	1.04	0.90
30'	-0.09	1.37	-2.12	1.39	0.17	0.88
50'	4.02	1.31	1.17	1.18	1.06	0.79
60'	0.70	1.37	0.14	1.37	0.60	0.87
80'	2.31	1.33	-0.19	1.27	0.72	0.81
40 mph						
20'	23.07	2.47	-3.98	0.59	1.14	2.20
30'	0.27	1.16	7.40	1.03	0.86	0.53
30'	-2.23	1.19	-6.97	0.64	0.06	1.75
50'	7.06	1.17	2.07	0.61	0.96	1.07
60'	-1.03	1.12	-1.06	0.71	0.44	1.00
80'	3.08	1.14	-1.84	0.59	0.61	1.24
60 mph						
20'	51.62	5.61	-6.77	1.60	1.01	1.30
30'	-2.66	1.39	14.06	1.97	0.84	0.80
30'	-4.80	0.87	-13.92	0.89	-0.16	1.07
50'	11.10	1.33	3.99	1.62	0.91	0.97
60'	-3.76	0.72	-3.25	1.22	0.33	0.76
80'	4.15	0.78	-4.18	1.11	0.50	0.84
80 mph						
20'	119.39	13.94	-9.57	1.54	4.54	4.47
30'	-4.46	1.88	27.66	0.57	1.87	2.17
30'	-6.50	1.95	-21.60	0.90	2.71	2.23
50'	20.22	2.31	8.82	1.15	2.83	0.98
60'	-5.52	1.27	-4.29	0.82	2.25	0.78
80'	8.12	1.31	-5.69	0.92	2.77	0.98

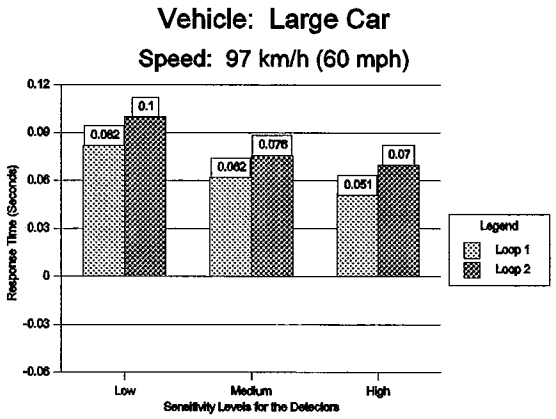
Table B-2. Comparison of Average Error and Standard Deviation for Different Detector Orders for a Pickup Truck

Speed and Trap Distance	Detector Order A,B,C,D		Detector Order C,D,B,A		Detector Order A,A,A,A	
	Average Error (mph)	Standard Deviation	Average Error (mph)	Standard Deviation	Average Error (mph)	Standard Deviation
20 mph						
20'	6.27	1.42	-1.11	0.76	1.26	0.66
30'	1.31	1.20	2.41	1.23	1.53	0.87
30'	0.14	1.29	-1.55	0.93	1.19	1.18
50'	3.05	1.22	0.85	0.97	1.42	0.77
60'	0.71	1.23	0.17	0.83	1.36	1.01
80'	1.86	1.23	-0.13	0.86	1.33	0.90
40 mph						
20'	20.21	2.31	3.01	0.71	0.84	1.38
30'	-0.51	0.94	6.78	0.87	1.26	0.55
30'	-2.33	1.20	-6.47	1.09	0.41	1.10
50'	5.81	1.01	2.29	0.75	1.08	0.56
60'	-1.45	0.99	-1.10	1.07	0.82	0.66
80'	2.38	0.97	-1.48	0.89	0.82	0.60
60 mph						
20'	57.45	5.99	-6.50	2.38	1.85	2.05
30'	-1.71	1.46	16.17	4.02	2.04	1.80
30'	-3.57	1.46	-14.63	3.44	0.01	2.34
50'	13.07	1.63	5.19	0.83	1.93	1.06
60'	-2.67	1.16	-3.22	1.18	0.98	1.63
80'	5.80	1.40	-3.87	1.53	1.17	0.92
80 mph						
20'	95.84	9.91	-7.88	2.31	2.62	3.86
30'	-4.21	1.66	23.17	0.55	2.39	1.46
30'	-5.51	1.15	-19.55	0.78	1.20	3.16
50'	17.38	1.92	7.86	1.49	2.44	1.74
60'	-4.88	0.77	-4.55	0.86	1.75	1.34
80'	7.19	0.61	-5.01	1.06	1.95	1.82

12.0 APPENDIX C

GRAPHS OF RESPONSE TIME STUDIES





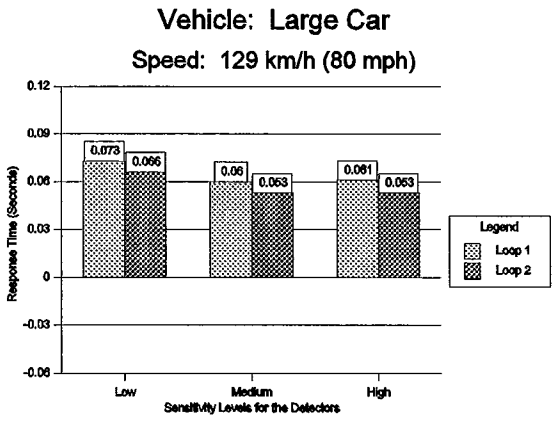
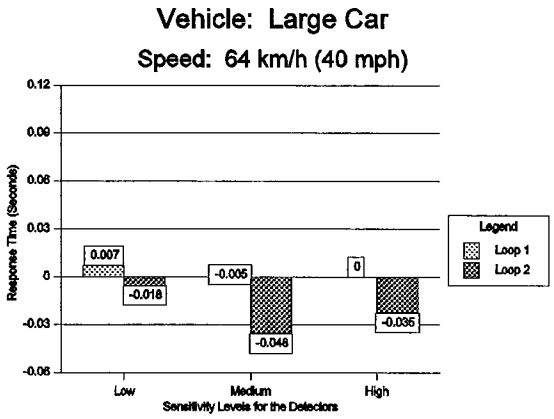
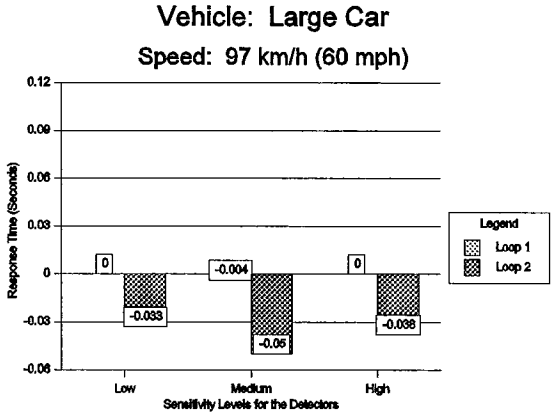


Figure C-1. Mean Response Times for Detector Systems Detectors (Large Car)





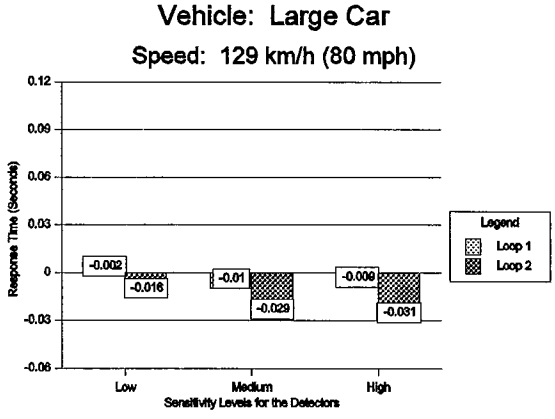
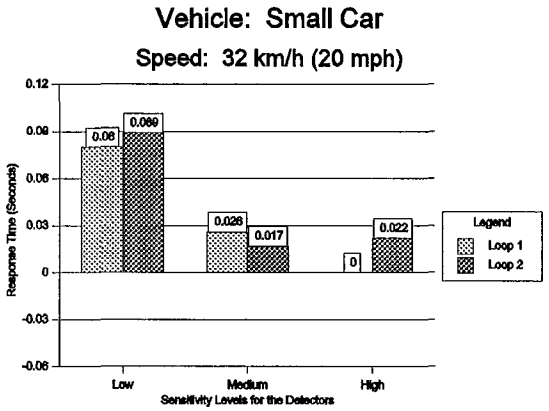
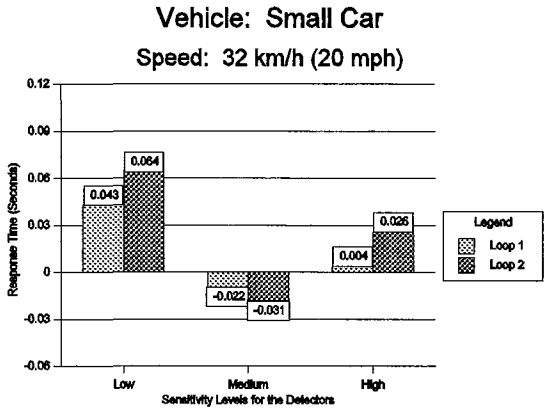
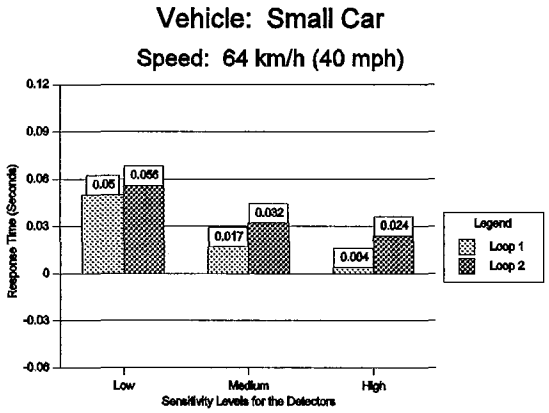
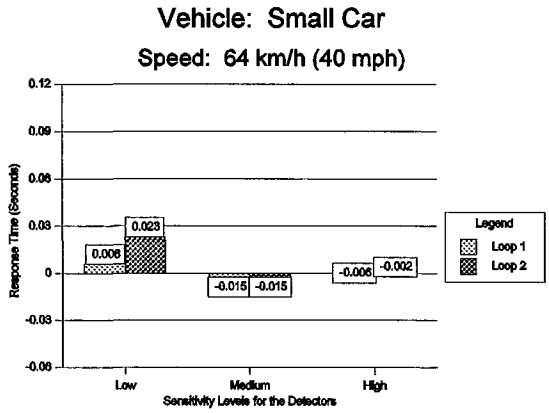


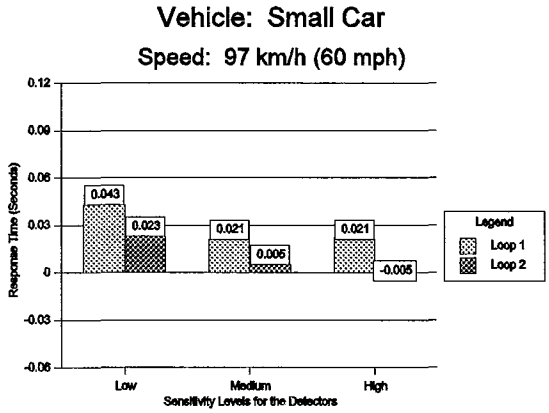
Figure C-2. Mean Response Times for Naztec Card Rack Detectors (Large Car)











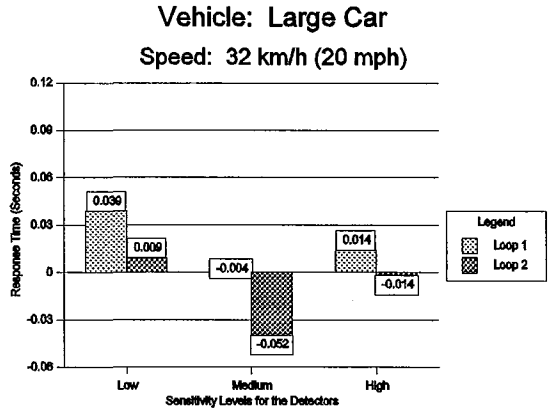
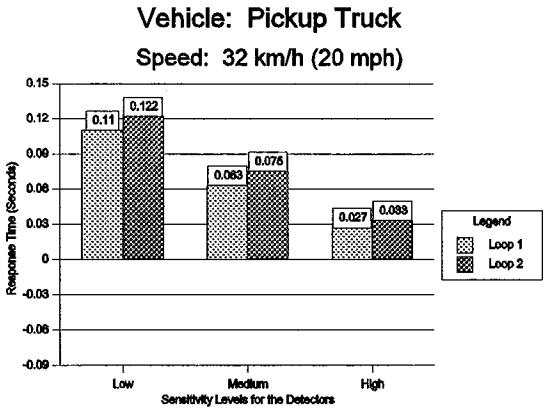
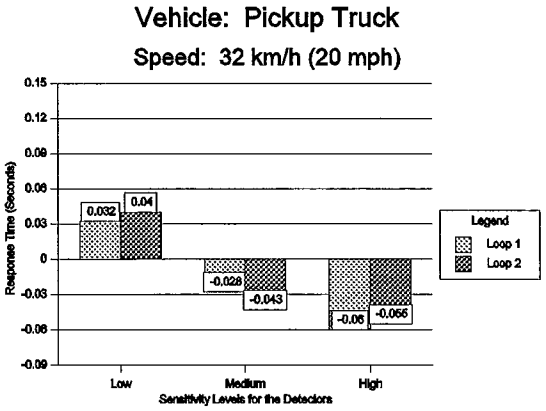
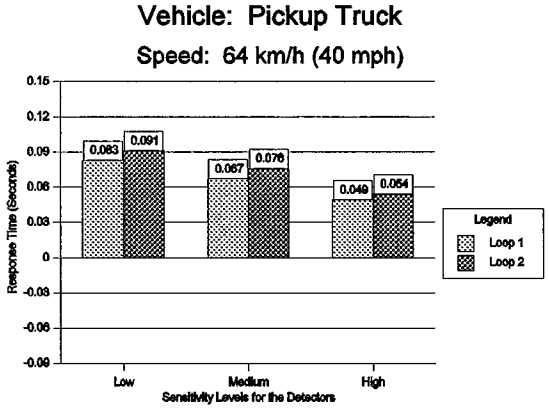


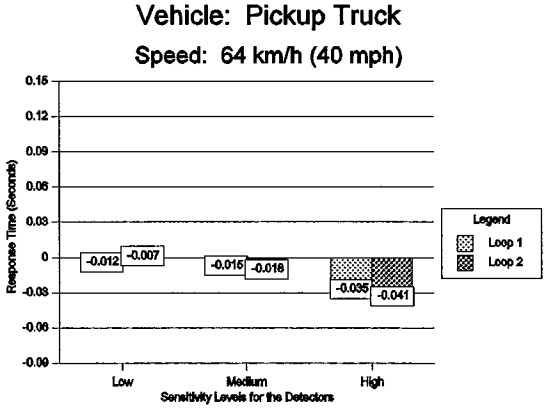
Figure C-3. Mean Response Times for Detector Systems Detectors (Small Car)

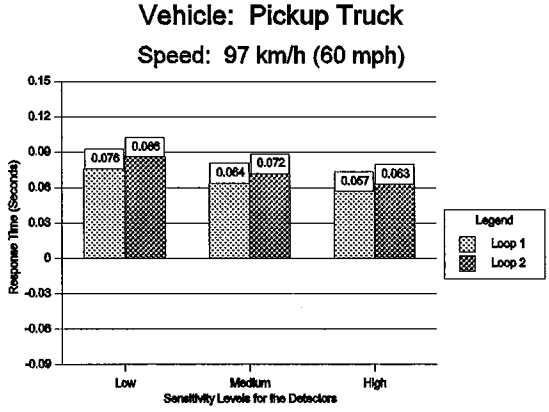
Figure C-4. Mean Response Times for Naztec Card Rack Detectors (Small Car and Large Car at 32 km/h)











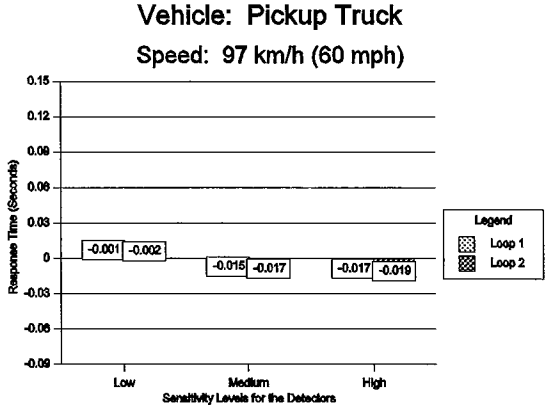
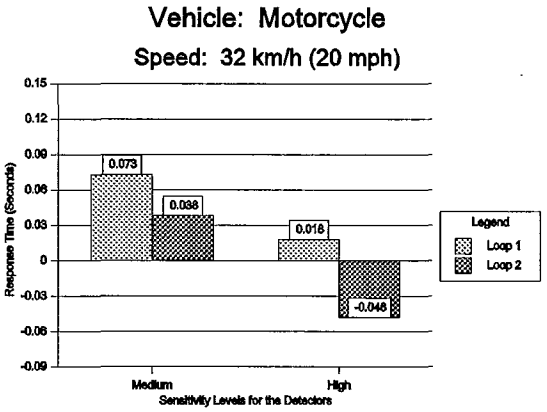
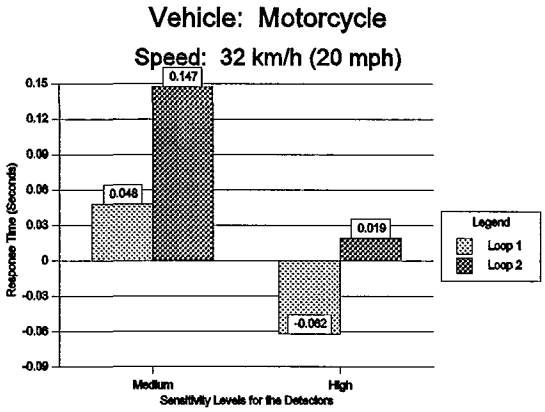
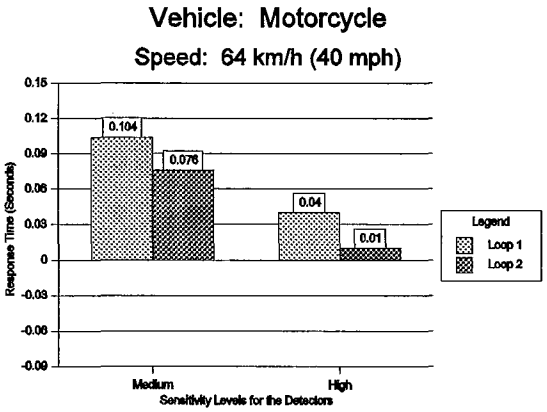


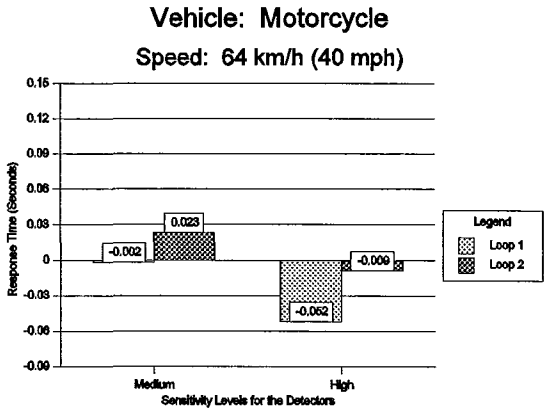
Figure C-5. Mean Response Times for Detector Systems Detectors (Pickup Truck)

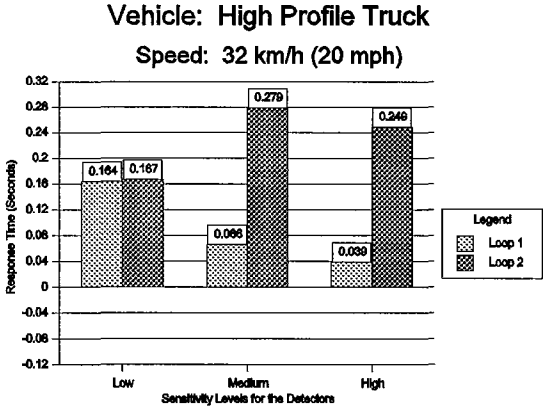
Figure C-6. Mean Response Times for Naztec Card Rack Detectors (Pickup Truck)











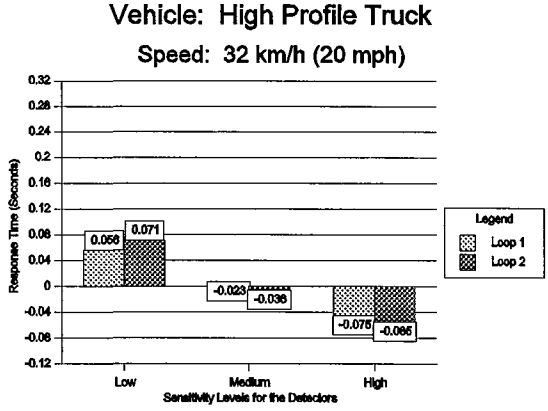
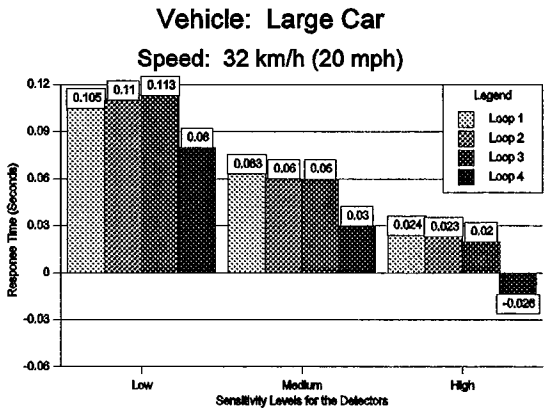
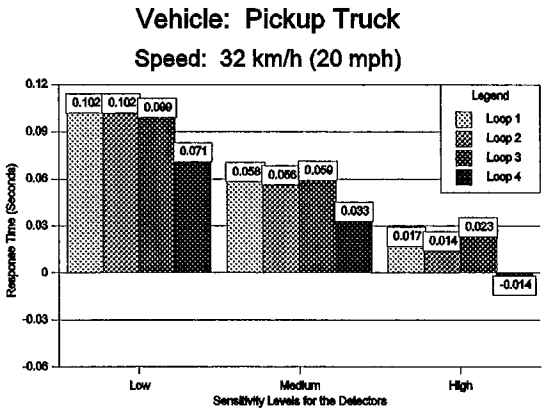
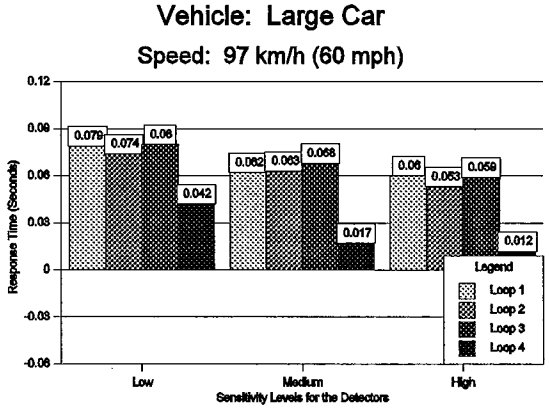


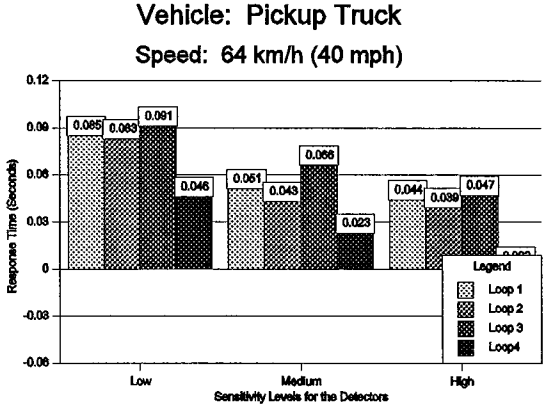
Figure C-7. Mean Response Times for Detector Systems Detector (Motorcycle and High Profile Truck)

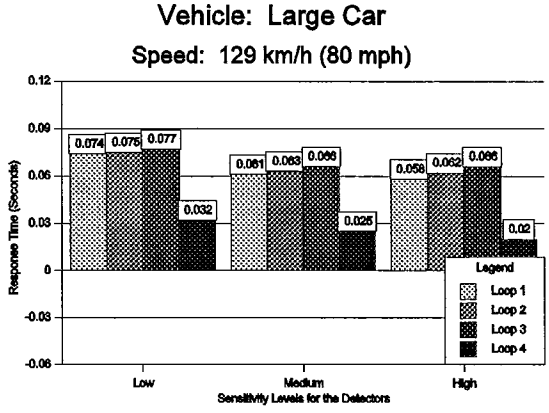
Figure C-8. Mean Response Times for Naztec Card Rack Detectors (Motorcycle and High Profile Truck)











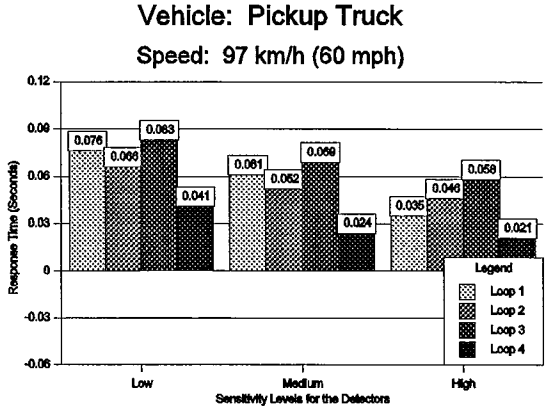


Figure C-9. Mean Response Times for Single Conductor Wire Loops (Loops 1, 2, 3) Versus Multiconductor Cable (Loop 4)

Figure C-10. Mean Response Times for Single Conductor Wire Loops (Loops 1, 2, 3) Versus Multiconductor Cable (Loop 4)