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16. Abstract

The research documented in this report analyzed detection capabilities of a trip-wire video image processing system in a freeway setting. Count and speed accuracy, as well as occlusion, were parameters of interest in field testing at Texas A&M University's Riverside Campus research facility. Testing analyzed three camera heights, 9.1 m (30 ft.), 12.2 m (40 ft.), and 15.1 m (49 ft. - 6 in.), in conjunction with three passenger car speeds, 32 km/h (20 mph), 72 km/h (45 mph) and 88 km/h (55 mph). The video image processing system used in the study was the Autoscope™ 2004. The camera imaging device was a 12.4 mm (½ inch) interline transfer microlens charged coupled device (CCD), utilizing a 6 mm, f1.2 auto iris lens. An analysis of variance (ANOVA) test indicated that both camera height and travel lane location affected the system's ability to accurately detect passenger cars. Generally, higher camera heights and travel lanes farther from the camera produced accurate passenger car detection farther upstream from the camera, based on no traffic in other lanes closer to the camera. Also, passenger cars traveling in adjacent travel lanes did not always influence the video image processing system's ability to accurately detect passenger cars in this highly controlled environment. The paired *t*-test indicated that speeds determined by the video image processing system were significantly different from speeds obtained by radar. Tests at night revealed errors in counts, and daylight truck occlusion was worse than cars for all camera heights. Based on the cost information from Texas Department of Transportation, life-cycle costs of video detection are similar to the cost of detection by inductive loops where many individual loop detectors are replaced by one camera, as might occur at intersections. Motorist delay may cause a different outcome. Where fewer loops are replaced by one camera, as on freeways, the additional investment for video detection will probably not be cost effective.

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ASSESSING VEHICLE DETECTION UTILIZING VIDEO IMAGE PROCESSING TECHNOLOGY

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IMPLEMENTATION STATEMENT

Findings of this research include pertinent information related to camera mounting locations, limitations of video detection technology, and cost information related to replacing inductive loop detectors with video. Optimizing detection accuracy requires close scrutiny of camera mounting heights, camera position relative to traffic, and camera optics. Generally, higher camera heights and travel lanes farther from the camera produced accurate passenger car detection farther upstream from the camera. Camera heights of 12.2 m (40 ft.), are recommended for improved detection and increased speed accuracy. The designer must also consider camera angle and camera optics to maximize video system efficiency rather than consider only camera height.

Detection accuracy in lanes farthest from the camera also relied upon proper positioning of detectors used by the AutoScope video processor. For example, if lane 6 detectors are placed too close to the lane line separating it from lane 5, the AutoScope double counts vehicles -- once in lane 5 and again in lane 6. Close scrutiny of video detectors in the field using a monitor after setup (in this case, during the office replay) for a reasonable period of time should provide needed insight into required adjustments.

For speed detection, a camera height of 12.2 m (40 ft.) is better than 9.1 m (30 ft.), but 14.1 m (49 ft. - 6 in.) is only slightly better than 12.2 m (40 ft.). Overall, *unadjusted* AutoScope speeds showed greater differences from radar than desired. Ranges in speed differences extended from approximately 15 percent to as high as 23 percent, with the greatest error at the lowest camera height of 9.1 m (30 ft.). Unadjusted AutoScope speeds were always higher than speeds obtained by radar. Sources of speed error in video detection include the bias caused by detecting the top of the vehicle (but calculating speed based on detections at ground level), pixel resolution limits, and the processing speed of the system at 30 frames per second.

Video detection should not currently be considered as effective in some adverse weather and lighting conditions as in optimum conditions. Study results of a truck-car pair at close intervehicle spacings at night show that vehicle counts by the AutoScope 2004 are not accurate, possibly due to headlight reflections from cars onto the truck. Vehicle counts and speed correlation between video and radar were worse during non-midday tests compared to optimum lighting conditions. Results of sunrise tests of four cars indicate little or no effect of a low sun angle on system operations. However, it should be noted that haze significantly reduced the sun's intensity on both mornings when testing occurred. According to interview information gathered during the study, CCD cameras should never be oriented to point directly at the sun.

An investigation of life cycle costs of video image processing systems and inductive loop systems indicate that several variables affect the relative costs of these competing systems. These variables include: initial costs, maintenance costs, traffic control costs (during installation and maintenance activities), and motorist delay costs. Life cycle costs of video and inductive loops were similar for intersections in Paris where one camera could replace several loops. However, in a freeway situation with fewer loops, the result favors loops. On an assumed six-lane freeway, for example, one video processor and two cameras could replace six loops in each direction, resulting in loop costs that are considerably less than video.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation or of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. The engineer in charge of the project was Dan Middleton, P.E. # 60764.

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SUMMARY

Problems with inductive loop detectors (ILD) have led various jurisdictions, not just in Texas but throughout the nation and beyond, to begin to investigate other technologies for vehicle detection. Vehicle detection is absolutely critical to efficient and effective traffic surveillance and control, yet it remains one of the weakest links. Problems with currently used ILDs include lack of flexibility, weakening of pavements that sometimes results in failure of the loop, and the disruptive aspects of installation and repair, causing motorist delay and excess fuel consumption. Even with these problems, most jurisdictions continue to use loops. This may be simply because there is a sufficient knowledge base to install and maintain loops, or because other detection technologies such as video detection have not fully proven themselves as viable alternatives. Positive elements of video detection technology include: direct measurement of important traffic parameters (e.g., density), flexibility in detector location, multiple uses of camera images, its "high-tech" appeal, and keeping agency forces off the roadway and out of harm's way.

This research included field tests using an Autoscope 2004 unit in a freeway setting, development of a procedure for determining the camera location using Microstation software, and a cost study to compare life cycle costs of inductive loop detectors and video detection. To determine a camera's coverage area, researchers developed three-dimensional views on a desktop computer to emulate the view of a camera. These views can be used to assist designers in the camera location process to reduce costly and time consuming field activities. These views are based on imager size, focal length, and camera height/offset information. The cost study used information gathered from TxDOT districts to determine ILD costs and information from the Road Commission of Oakland County, Michigan to determine video detection costs.

Statistical testing of field data included the effects of occlusion (hiding of a vehicle by another vehicle closer to the camera) and the effects of vehicle speed and camera height on detection accuracy. Some of the field study activities apply to intersections, but the primary focus was freeways. The field test setting was a controlled environment in which vehicle pairs operated through an established detection zone replicating one direction of a 12-lane freeway with the camera at 5.3 m (17.5 ft.) from the inside edge of lane 1 and 9.1 m (30 ft.) from the inside edge of lane 2. Camera heights were 9.1 m (30 ft.), 12.2 m (40 ft.), and 15.1 m (nominally 50 ft.) Vehicle speeds were 32 km/h (20 mph), 72.4 km/h (45 mph), and 88.6 km/h (55 mph). Intervehicle spacing in all tests corresponded to a 1.5 second headway. Most of the testing in this freeway setting used only optimum midday lighting conditions. However, a smaller sample of tests evaluated the effects of darkness, occlusion by a large truck, sunrise with the camera facing the sun, water on the pavement, and long shadows cast across the detection area by passing vehicles or by other objects adjacent to the roadway. The camera used in all tests was a 6 mm (¼ in.) fixed focal length charged couple display (CCD) camera with 12.2 mm (½ in.) imager. All statistical tests that used a predetermined alpha value established its value at 0.05, corresponding to 95 percent confidence in the decision.

occlusion by passenger cars. These findings are followed by cost findings, comparing inductive loop costs to video detection. At the 32 km/h (20 mph) passenger car speed, each camera height was significantly different from other camera heights. However, analyzing the individual camera height-travel lane data sets using the Bonferroni test revealed that some camera height-travel lane data were within the same statistical grouping. This mixed finding somewhat corroborates another detail — a 15.1 m (49 ft. - 6 in.) camera height yielded results only infinitesimally better than the 12.2 m (40 ft.) height. In practical terms, they were the same. Another general finding was that the detection distance increased as the lane offset increased. This phenomenon was due to the occlusion effects of the first passenger car.

The fixed 1.5 second headway provided a sufficient gap for passenger car speeds of 72 km/h (45 mph) and 88 km/h (55 mph) for the AutoScope system to consistently detect (count) two passenger cars at a distance of 121.9 m (400 ft/) away from the camera. Actual detection distances were greater than 121.9 m (400 ft.), but exact distances were not measured.

The hypothesis that vehicle speeds determined by the AutoScope system and those determined by radar were the same was rejected. Comparing the *unadjusted* mean speed values from speeds determined by the AutoScope system and the mean speed values from the speeds obtained by radar revealed a fairly constant percent difference for a given camera height, regardless of the passenger car speed. The percent differences in passenger car speed were from approximately 23 percent for a camera height of 9.1 m (30 ft.), approximately 16 percent for a camera height of 12.2 m (40 ft.), and approximately 15 percent for a camera height of 15.1 m (49 ft. - 6 in.) Again, camera mounting heights of 12.2 m (40 ft.) and 15.1 m (49 ft. - 6 in.) were practically the same. *Adjusted* AutoScope speeds were still statistically different from radar in some comparisons.

Some statistical comparisons resulted in rejection of the null hypothesis that vehicles in lane 5 influenced the system's detection ability in lane 6. The variability of the data is attributed to factors other than vehicle influences (occlusion) from travel lane 5. These factors include: reflections from the vehicle, electronic "noise," shadows, or cloud cover. Larger vehicles in the foreground had an even greater propensity to hide smaller vehicles from view, perhaps resulting in a different outcome.

Findings generated by non-midday tests were less conclusive due to not operating in all lanes used in midday tests. Sample sizes in each lane still used an alpha value of 0.05, for a 95 percent confidence interval. The AutoScope detector uses a different technique for day versus night detection. The system detects headlights at night versus detecting the body of the vehicle during daylight. One positive finding was that vehicles were generally detected at night at greater distances at the same camera height and vehicle speed as compared to daylight. The night tests generally produced more accurate speeds from lanes farther from the camera than closer lanes. Vehicle counts were inaccurate in car and truck tests at night. Night tests detected only one vehicle in each lane (instead of two), perhaps due to the amount of glare generated by both sets of headlights, reflections of car headlights on the truck, or short headways. Additional testing should be done with a large vehicle closer to the camera (e.g., in lanes 1 and 2). Careful observation of the video replay indicated that the detector did not clear until all four vehicles were past. Insufficient data exist for determining a detection range from truck runs because neither of the setups in lanes 1-2 or 5-6 detected properly. Truck speeds were more accurate at 32 km/h (20 mph) than 28 km/h (45 mph) but both were significantly different from radar speeds. The night wet pavement AutoScope speed was slightly less accurate than the daytime dry pavement AutoScope speed.

The final area of analysis involved a comparison of the costs of inductive loops and video image processing systems. Both the Houston District and the Paris District of the Texas Department of Transportation provided recent installation costs and related information at *intersections*. Using this as a starting point, an analysis compared life cycle costs of operating a video system for intersections compared to the same costs for a loop system. The present worth of a video system for a time period of 10 years would be between $40,036 and $48,982. The present worth of installing and operating a loop system for 10 years would be between $42,119 and $44,678. The range is due to variability in available data. Neither analysis considered salvage value, but both systems are assumed to have similar lengths of useful life beyond the 10-year time frame. Variables that must still be evaluated for inductive loops are motorist delay and excess fuel consumption during installation or repair. This additional cost for inductive loops could increase the life-cycle costs of loops such that they are considerably more expensive than video detection.

For an assumed six-lane *freeway*, cost calculations assumed a 3 percent rate as used elsewhere, resulting in a life-cycle loop cost in a 10-year present worth analysis of $7,692. Costs of a replacement video system would consist of a processor and two cameras, costing approximately $18,000 and $3,000, respectively. Ancillary equipment such as mounting hardware and cabling was estimated at approximately $500 per camera. Installation costs for cameras, processor, and other hardware were estimated at $300. The total life-cycle cost of a video system at a freeway location to monitor one direction of traffic would be $13,032. This is considerably more expensive than the loop system, assuming similar salvage values for both systems.

1.0 INTRODUCTION

Urban freeways are the backbone of the highway transportation system and the demand on this system is growing. This increased demand creates an increase in traffic congestion. New freeway construction and widening have been past solutions to relieve congestion. However, these solutions are less viable due to the rising cost of acquiring right-of-way, environmental concerns and constraints, and regulations that require a reduction in the total vehicle miles traveled (*1*). Effectively managing the operations of the existing transportation network is an alternative for congestion mitigation.

The ability to detect the presence of a vehicle or accurately count the number of vehicles on the freeway is critical in determining the current operating condition. Promptly and adequately responding to traffic congestion allows the transportation engineer to maintain the best possible level-of-service on the facility. Advanced technologies and improved equipment are available to improve traffic control and traffic management objectives (*2*).

Vehicle detection is currently one of the weakest links in traffic surveillance and control. Current detection equipment also has limited capabilities and reliability issues (*2*). The most widely used vehicle detection method is inductive loops that are placed in the pavement surface. However, existing loop detector systems have been unreliable for several reasons. Loop detectors are unable to measure certain traffic parameters important to assessing traffic conditions accurately. Traffic measurement parameters, such as speed, traffic composition, and queue length, are derived from vehicle presence or passage requiring multiple detection (*2*). Installation and maintenance of an inductive loop detector system to collect this type of traffic data is expensive. Furthermore, this type of detection system does not have visual surveillance capabilities or placement flexibility (*2*).

More reliable, economic, and flexible detection methods are needed. Vehicle detection through video cameras is one of the most promising new technologies available for large scale data collection and traffic management (*2*). These systems have several advantages. A single system can replace several loops enabling traffic detection in multiple locations within the camera's field-of-view. The detector locations in the system can be easily removed or adjusted following initial placement (*3*). The structural integrity of the roadway pavement is not compromised and traffic disruption, due to loop detector installation or maintenance, is eliminated because the detector location does not exist in the pavement.

1.1 PROBLEM STATEMENT

Effective congestion management requires reliable and current traffic condition information. Reliable traffic information is dependent upon accurate vehicle detection. The better "picture" the transportation engineer has of the freeway, the quicker an appropriate strategy can be implemented. To have a continuous "picture" of the traffic stream requires numerous, closely spaced loop detectors.

Video image processing is a rapidly advancing technology. The capabilities and limits are ever changing. Adapting a system to fit current and future needs is critical in implementing effective traffic management measures. The tests conducted for this report establish some basic detection parameters and limits. The information gained from these tests can be utilized to determine general design guidelines for placement of a video image system.

1.2 RESEARCH OBJECTIVES

The objective of this research is to assess the potential of video image technology to accurately detect vehicles in a freeway condition. This assessment determines the limits a video image system has in accurately counting vehicles and determining vehicle speeds. The limits obtained in this study provide guidance in design and location of video image systems. These guidelines will aid transportation agencies to properly place video image detection systems in the field to achieve the intended purpose. The following tasks were performed to satisfactorily accomplish the research objectives.

1. Review pertinent literature and research concerning existing vehicle detection systems and the status of video image technology.

2. Establish a method of procedures to determine the detection limits of a video image processing system.

3. Collect vehicle counts and speeds at three camera heights utilizing the Autoscope video image processing system.

4. Analyze the vehicle counts and speeds and determine the relationship between the detection limits and camera height.

5. Provide guidance for optimizing video image camera placement for freeway applications.

1.3 ORGANIZATION OF REPORT

This report is divided into five chapters. Chapter I includes the introduction, problem statement, and research objectives. Chapter II identifies various vehicle detection systems utilized today and presents the status of video image technology. Chapter III includes the experimental study design, procedures describing the selection of the study site, and discusses the parameters investigated. Chapter IV describes the analysis and reduction of the data collected from the study. Chapter V presents the conclusions, recommendations, and concerns surrounding this research. Directions for further research are also presented in Chapter V.

2.0 BACKGROUND

2.1 INTRODUCTION

Traffic management is taking a more active role in the operations of the highway transportation infrastructure. Processing and evaluating traffic information concerning traffic congestion and travel times allows transportation agencies to implement traffic management strategies in a more efficient manner, reducing delay and user cost. Effective traffic management begins by accurately detecting vehicle presence. This chapter presents current accepted vehicle detection methods and provides the state of practice for video image processing as an alternative to current detection methods and procedures.

2.2 TRAFFIC MANAGEMENT

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and the Clean Air Act Amendments of 1990 (CAAA) have placed emphasis on traffic management strategies to reduce the vehicle kilometers (miles) traveled in major metropolitan areas. These traffic management strategies vary depending upon the current traffic conditions and the type of traffic congestion. Traffic congestion types include:

- peak period and other recurring congestion,
- nonrecurring congestion (incidents),
- special events,
- construction and maintenance work zones,
- inclement weather, and
- catastrophic events (earthquakes, hurricanes, etc). (*1*)

Nonrecurring traffic congestion or incident management strategies include: detecting the incident, verifying that the incident has occurred, responding with emergency vehicles and information, and clearing the incident and monitoring the traffic stream until traffic returns to normal operations (*4*). All types of freeway congestion reduce the capacity of the freeway segment (*2*).

Proper traffic management strategies cannot be implemented unless or until congestion is detected. An essential element in managing freeway traffic and implementing traffic management strategies is traffic surveillance. A traffic surveillance system monitors traffic conditions and collects information for implementing control measures. Effective traffic management strategy implementation depends on the reliability and accuracy of the detection system (*1*). Prompt detection and response reduces vehicle delay and user cost. Vehicle detection is the weakest link in traffic surveillance and control (*2*). Additionally, real-time data is required to bring traffic management to the next level. This level strives to reduce congestion, reduce congestion time, and reduce the response time in mitigating incidents.

2.3 CURRENT DETECTION METHODS

Traffic detection has been utilized to obtain useful traffic information for many years. Pneumatic tubes, "electric-eye" optical, and magnetic detectors were first used in the 1930s. Inductive loop, infrared, ultrasonic, radar, and photoelectric systems emerged in the 1960s, with the inductive loop system becoming the predominant system by the 1970s (*5*).

Detectors recognize the presence of a stopped or moving vehicle, identify the passage of a moving vehicle by completing a circuit or detect changes in an electrical or magnetic field. Most detectors are composed of three components: the sensor, the lead-in cable, and the interpreter/receiver (*1*). Detectors also collect or derive traffic volumes, vehicle speed, lane occupancy, density, and queue lengths. These parameters are used to derive levels of congestion, incidents, and delays. Successful implementation of automatic detection and control systems depends on the systems's reliability (*6*).

Current detectors are placed on or embedded in the pavement, or they are mounted off the roadway. Therefore, they can be classified as 1) pavement detectors and 2) off-roadway detectors. The first category of detectors embedded in the roadway pavement are both subject to pavement weaknesses and are a likely cause of pavement weakness. They are exposed to extreme weather conditions, deicing chemicals in some areas, and they are often damaged by utility work. Maintenance of these types of detectors is labor intensive and disruptive to the motorist (*1*). The second category of detectors is generally *non-intrusive* in terms of traffic disruption. Each type of detector system is discussed below in more detail.

2.3.1 Pavement Detectors

2.3.1.1 Inductive Loop Detector Systems

Inductive loop detectors (ILD) are the most widely used traffic detector system. ILDs operate by creating a magnetic field from an electrical current passing through wires embedded in the pavement (*1*). Energy is absorbed by a vehicle passing over the detector. This absorbed energy causes a frequency change in the tuned loop circuit. The frequency change is interpreted by loop amplifier electronics as a vehicle "presence" in the detection zone (*7*).

An inductive loop detector is composed of three parts: the loop, the lead-in cable, and the detector unit. The *loop* is a coil of wire embedded in, or placed on the roadway pavement. The *lead-in cable* connects the loop to the detector unit and consists of two types of cable. The first cable type is the loop cable. The loop cable connects the loop to the pull box and is the same type of cable used to form the loop itself. The second cable type is the shielded cable. The shielded cable connects the loop to the detector unit. The *detector unit*, or detector amplifier, is the electronic circuitry interpreting the changes in the electrical properties when a vehicle passes through the loop (*8*).

An inductive loop detector system operates in one of two modes, pulse or presence. In the pulse mode, the signal sent by the detector unit lasts for a very short duration. The signal in the presence mode lasts as long as the vehicle is in the detection area. The mode used in most detection applications is the presence mode (*8*). Loop detector shapes vary with the type of vehicle being detected. Square, rectangular, skewed, and triangular are the four general loop detector shapes with the square and rectangular being the most commonly used shapes (*7*). The most effective loop geometry is dependent on the type of vehicle detection required (*9*). Vehicle detection and counting is determined by utilizing one inductive loop embedded in each travel lane. Vehicle speeds are determined by placing two inductive loops at a known distance apart (*7*). The distance between the loops divided by the time required for the vehicle to travel between the loops determines the speed of the vehicle.

Inductive loop detector systems sometimes incorrectly count and/or classify large trucks. Tractor-semitrailer vehicles are sometimes problematic because the height of metal at intermediate points may exceed the height of inductance flux lines. Loop detectors sometimes mistake this phenomenon as two closely spaced smaller vehicles. Motorcycles are another vehicle type often not detected by rectangular inductive loop detectors. Improvements to the detection algorithm have overcome some of these occurrences. (*5*).

Proper installation of the loop in the road surface is important to improve the reliability of the system. Some pavement surfaces, such as bridge decks, preclude the saw cutting necessary to install permanent ILDs. A primary disadvantage of ILDs is the expense of relocating or repairing loops after installation, requiring extensive traffic control and resulting in motorist delay (*9*). Detector "cross-talk" and increased pavement stress are two additional disadvantages of inductive loop detector systems. Additionally, several adverse conditions that affect the operation of ILDs 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 cost (*7*). An advantage of ILD systems is their ability to operate in all weather and lighting conditions (*9*).

Inductive loop systems may fail for a variety of reasons. These reasons are not due to the concept of the inductive loop, but to the manner in which the loop system is installed, poor maintenance, or pavement failures. Improperly applied weather sealant, poor wire connections, and pavement expansion and contraction are a few factors that cause inductive loops to fail. Repair of failed systems is costly, resulting in motorist delay and hazards during maintenance operations for both motorists and maintenance crews (*5*).

There are differing opinions on the reliability of inductive loop systems. Some agencies believe that inductive loop technology is the best available, while others claim that ILDs malfunction so often that they are not worth repairing (*5*). One study interviewed several California Department of Transportation (Caltrans) personnel. These Caltrans personnel indicated that approximately 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 (*5*). Such programs are costly, but maintaining a low failure rate requires them.

Bikowitz (*10*) et al., analyzed a number of New York State Department of Transportation's (NYSDOT) 15,000 inductive loop detectors and found that loop failures were caused mainly by improper installation, inadequate loop sealants, or wire failure. The study revealed several installation processes that 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. The study recommended several improvements to NYSDOT's installation process and procedures for installing inductive loop detectors.

A study by Chen (*6*) et al. conducted in Los Angeles revealed that up to 15 percent of the 115 detectors analyzed were unavailable, and between 2 and 11 percent showed error flags during the experiment. The causes of the detector failures included moisture, loop sealant deterioration, pavement cracking, broken wires, deteriorated insulation, corroded splices, and detuned amplifiers.

Labell (*5*) et al. compared loop detector counts with visual counts. This study was conducted near the Caldecott tunnel near San Francisco. Preliminary data from this study indicated discrepancies as high as 20 percent between visual counts and ILD counts. Further investigation revealed that an overload on the power source significantly affected the operation of the loop detectors. Final analysis concluded that the ILD system, when operating properly, was accurate. Improvements in the materials used in the installation of inductive loops have increased the reliability of these systems (*5*).

2.3.1.2 Microloop Detection Systems

A microloop detection system is a passive sensing system based on the earth's magnetic field. A vehicle passing through the detection zone temporarily distorts the earth's magnetic field. This magnetic field change creates an electrical circuit change in a specially designed circuit in the microloop (*7*). The advantages of microloop detection systems over inductive loop systems are speed of installation, installation below the pavement in the subgrade, thereby not degrading the integrity of the pavement, and less wire needed to create the loop (*7*). Disadvantages of microloop systems include installation difficulties (consistent with specifications) and the narrow effective width of the detection field, requiring several probes to detect a variety of design vehicle types (*7*).

2.3.1.3 Magnetometer Detector Systems

Magnetometers were developed in the 1960s and operate similar to ILD systems (*5*). Magnetometer detector systems consist of small cylinders of sensor coils placed in a small hole underneath the pavement in the center of the travel lane. Magnetometers detect an increase in the vertical flux lines of the earth's magnetic field caused by a vehicle passing through the detector field (*8*). Magnetometers are easier to install than ILDs and are useable in isolated locations where inductive loop detectors are impractical, such as on bridge decks (*5*). The disadvantages of magnetometers are similar to those of ILDs. They sometimes double count trucks, and are less likely to detect motorcycles due to their small detection zone (*5*).

2.3.1.4 Magnetic Detector Systems

Magnetic detectors consist of several dense coils of wire wound around a magnetic core. This core is placed in or underneath the pavement. Magnetic detector systems operate in the same manner as magnetometer detector systems and ILDs (*8*). The disadvantage of magnetic detector systems is their inability to detect stopped vehicles; detection requires motion. Also, placing two magnetic detectors too close together can result in interference between the two detectors (*5*).

2.3.1.5 Piezoelectric Axle Sensors

Piezoelectric sensors are a film consisting of a crystalline form of long hydrogen, carbon and fluoride polymer molecular chains. The crystalline chain produces an electrical charge when a mechanical strain occurs, when a vehicle passes over the film (*11*). One advantage of piezoelectric sensors is their ability to be utilized as weigh-in-motion detectors. Piezoelectric sensors serve as axle sensors, so they can be used to distinguish between vehicle types (*9,11*). Modern vehicle classifiers typically use a combination of piezo sensors and ILDs to count and classify vehicles in a user-definable classification scheme. One disadvantage of temporary piezoelectric sensors mounted on the pavement surface is their limited durability (*11*). Piezoelectric sensors are becoming more extensively used in the United States.

2.3.1.6 Pneumatic Tubes

Pneumatic tubes are hollow rubber tubes connected to an air pressure transducer, that are stretched across the roadway. The air pressure increases as the wheel of a vehicle passes over the tube. The air pressure transducer senses the air pressure change and records the event (*8*). The advantages of pneumatic tubes are their low installation cost, simple and quick installation and removal, availability, and ability to be used in almost all weather conditions (*8, 9*). There are some reliability concerns regarding pneumatic tubes. Vehicles changing lanes, weaving, or entering and exiting the roadway could produce counting errors. Multi-axle vehicles also produce vehicle counting errors (*9*). Pneumatic tubes can easily be destroyed by vehicles and are only used in light traffic conditions (*8*).

2.3.2 Off Roadway Detectors

Table 2-1 contains some of the currently available off roadway non-intrusive sensors as provided in reference *(12)*. These same devices have been, or will be tested as part of that research activity. In addition to a listing of the technologies, the table includes capabilities, costs, and additional equipment required to accomplish the stated capabilities.

2.3.2.1 Infrared Sensing Systems

Infrared sensors utilize a narrow beam of energy directed onto an infrared receptor. Vehicles are detected as they pass through the beam (*8*). There are two classes of infrared detectors — active and passive. Active infrared devices have been applied to the traffic detection arena in two primary modes. One requires a receiving cell to reflect the infrared wave back to the detector unit. If the beam is disrupted by vehicle passage, the sensor detects presence and perhaps speed if multiple units are used. Another more sophisticated application of active infrared technology that is available today provides for classification and size measurement of passing vehicles. This is the type described in Table 2-1 as an active infrared device. Preliminary testing by public agencies indicates very promising results for monitoring vehicle speeds and classifications. It appears to accomplish day/night transitions and other lighting conditions without significant problems. The only weather conditions that appear to be problematic for this device are heavy fog and heavy dust. The second type of infrared detector is a passive type detector. Passive detectors do not require a receiving cell. The vehicle's presence is detected by the change in the wavelength reflected off the pavement surface (*5*).

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 (*8*). The accuracy of older infrared sensors are apparently compromised by changes in light and weather conditions such as passing clouds, shadows, fog, and rain. Two literature sources also indicated that some of these systems may not be reliable under high volume conditions and are not able to provide vehicle counts, unless mounted vertically with one detector placed in each lane (*5, 8*).

2.3.2.2 Passive Acoustic Detection Systems

A recent addition to the list of non-intrusive detectors for highway detection is a passive acoustic device, developed in partnership with the U.S. Navy. 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 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, its speed accuracy

TABLE 2-1. Summary of Available Detectors [a]

TECHNOLOGY	VENDOR/PRODUCT	STATED CAPABILITIES	APPROX. COST	ADDITIONAL EQUIPMENT
Active Infrared	Schwartz Electro-Optics, Inc. Autosense I	volume, occ., density, speed, class, presence	$6,500	PC, mounting bracket
Passive Infrared	ASIM Engineering Ltd. (Switzerland) IR 224	volume, occ., presence	$1,400	PC with interface box and display software (optional)
Passive Magnetic	3M Microloop	volume, occ., presence, speed (with 2 sensors)	$500 - $800 [b]	
Passive Magnetic	Nu-Metrics NC-40, NC-90A G-1, G-2 (wireless)	NC-40: vol., occ., presence NC-90A: same + spd, class, length G-1: vol., occ., presence, temp. G-2: same plus speed, class, length	NC-40: $550 NC90A: $895 G-1: $975 G-2: $1,695	PC, computer interface ($450), software ($745) & protective cover ($158 NCs only)
Radar	EIS, Inc. RTMS X1	volume, occ., speed, presence, turning movements, classification	$3,500	PC for setup and for serial data (opt.)
Doppler Microwave	Microwave Sensors, Inc. TC-20/TC26B	volume, occ., (20 is short range) (26B is long range)	TC-20: $630 TC-26B: $375	
Doppler Microwave	Whelen Engineering Co. TDW 10/TDN 30	volume, occ., speed (TDW is wide beam), (TDN is narrow beam)	$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 (optional)
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] Adapted from Reference *(12)*

[b] Price is estimated or was not known.

was plus-or-minus 10 percent compared to ILDs. It does not currently do vehicle classification, but this addition is already being planned. Its power requirements are low, 5 to 6 watts, allowing the use of solar panels if needed. The cost of this sensor is $1,450 per unit, with one required per lane per detection location. This system also requires a controller card at a cost of $800. Each card can accommodate four sensors. Mounting requirements are a minimum of 6.1 meters (20 feet) overhead and 7.6 meters (25 feet) horizontal distance from the travel lane. It can be mounted in a side fire or parallel direction. According to available information, there is no interference due to inclement weather, other than very dense fog.

2.3.2.3 Ultrasonic Detection Systems

Ultrasonic detector systems are also mounted above the roadway, and they utilize electronic signal generation. Receiver units are mounted on the side of the roadway or above travel lanes. Vehicle detection occurs when an energy burst directed at the target is reflected faster than expected (*8*). The advantages of ultrasonic systems are similar to those of infrared sensor systems; however, ultrasonic systems require a high level of maintenance (*8*). Ultrasonic detectors are also sensitive to environmental conditions, and the conical detection zone may miss some vehicles (*5*). Studies of ultrasonic detectors found problems with controlling the conical detection zone (*5*). 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 (*5*).

Labell (*5*) et al., compared ultrasonic detectors with ILDs and concluded that 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. A possible explanation of speed variation is the fact 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 ultrasonic detectors closely matched the visually counted data. Modifications have since resulted in improvements to ultrasonic detectors, reducing some of the above problems (*5*).

2.3.2.4 Microwave and Radar Detection Systems

Microwave and radar detection systems utilize a microwave energy beam directed onto an area from an antenna along side or above the roadway (*8*). The signal sent by the system is intercepted by the vehicle and echoed back to the sensor (*5*). Vehicle detection is accomplished through detection of a Doppler phase shift (*8*). Installation and maintenance of microwave and radar detection systems are simpler than inductive loop systems. The disadvantage of microwave and radar systems is their inability to detect a stopped vehicle and measure occupancy (*5*). Microwave and radar systems are also expensive to purchase and operate due to Federal Communication Commission (FCC) licensing requirements (*8*).

2.3.2.5 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, processes this information. AVI systems have the capability to uniquely identify a vehicle passing through the detection area. This technology has a variety of uses as Intelligent Transportation Systems (ITS) technology advances (*8*). A primary use for AVI systems is for electronic toll collection. These systems electronically debit a special account when a vehicle passes through the toll booths. A related application for AVI systems is congestion pricing (*4*).

AVI systems are able to monitor traffic conditions by using vehicles as probes in the traffic stream. The AVI system thus tracks a "tagged" vehicle along a freeway, allowing data to be processed at a single point location, as well as over a length of roadway. These sophisticated systems utilize "read-write" capabilities, providing two-direction information flow and 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 (*4*). An AVI system can record headways and 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 (*4*). The major disadvantage of using an AVI system as a vehicle detection system stems from the limited number of vehicles equipped with transponders.

2.4 VIDEO IMAGE PROCESSING 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 was undesirable, so subsequent generations of systems allowed the detection area within the camera's field-of-view to be altered. This was accomplished by developing and improving the video image processing software. Real-time detection became available with these technological advances (*13*, *14*). Advanced video image processing systems, which are discussed in detail in the following section, can collect, analyze and record traditional traffic data, detect and verify incidents, classify vehicle types, and monitor intersections (*15*).

A video image processing 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 (*8*). Several steps are required to acquire, process, and interpret a video image. The first step is image acquisition through the camera system. The most widely used camera system is a Charged Coupled Device (CCD) camera sensor. The second step requires an analog-to-digital converter to transform the analog signal into a digital form for use by the computer. The third step involves processing the image; it eliminates unwanted noise and enhances edges, contrast, and motion (*15, 16*).

Video image processing is limited by the resolution of the image. The resolution is represented by the number of pixels within the image view. Pixel is short for "Picture Element" and represents the "*smallest area of a television picture capable of being delineated by an electrical signal passed through the system*" (*17*). A pixel is a two dimensional element representing a three dimensional image. The actual dimensions a pixel represents is a function of the pixel's location within the image. Pixels representing a portion of the image far from the camera may represent several meters, while pixels representing the portion of the image close to the camera may represent less than 0.3 meters (1 foot.) Figure 2-1 shows a representation of the camera's field-of-view.

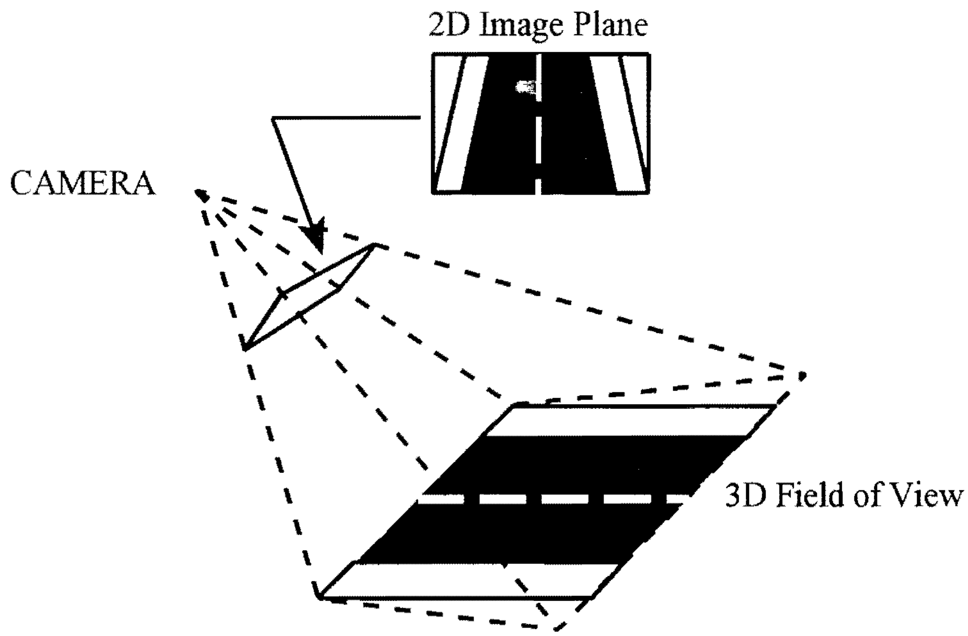

FIGURE 2-1. Video Image Camera's Field-of-View Representation.

Video image processing systems view the image as a set of pixels belonging to one of two categories. The first pixel category is *figure pixels*. Figure pixels are pixels that belong to the object of interest, such as a vehicle. The other category is the *ground pixel*. Ground pixels belong to the object's environment, or background (*16*). Video image processing systems "learn" the pixel intensity of the background, the part of the image that does not change or changes very little over time. When an object passes through the image, the system reacts to the changes in pixel intensity.

Processing a video image includes eliminating unwanted "noise" and enhancing edges, contrast, and motion. Unwanted "noise" is the electronic noise transmitted through the system. "Point noise" is the most common form of noise, where a single pixel has an unusually high or low value. This type of noise is reduced by analyzing surrounding pixels and averaging the pixels as a group (*15*). Edge detection and enhancement find areas in an image where the pixel values change abruptly. These abrupt changes generally occur at the boundaries of the image, such as a white car against a black pavement surface. Vehicle colors that are similar to their background cause problems with edge detection and enhancement techniques (*15*).

Contrast enhancement increases the dynamic range of the gray value in the image. Motion detection analyzes multiple images. Two images are compared pixel by pixel to find differences between them. Generally, the two images are divided; one image represents the background picture and the other image has vehicles in the image. Pixel intensities are compared between the two images, and the video image processing system groups the changed pixels into "blobs". Each blob corresponds to a vehicle. Processing speed of the image system becomes a concern when utilizing these processes. The more enhancement desired, the longer the time to process the image in the system. Limitations of the processing hardware must be considered when very high levels of accuracy and process ability are desired (*15*).

Two basic video image processing systems exist. The first type is classified as a "trip-wire" system. Trip-wire systems "*use a narrow line of pixels across a traffic image to detect passing vehicles.*" AutoScope by Image Sensing Systems, Camera and Computer Aided Traffic Sensor System (CCATS) by Devlonics Control, Traffic Analysis System (TAS) by Computer Recognition Systems, Aspex Traffic Analysis System (ATAS) by Aspex, Inc., and Tulip System by the University of Newcastle-upon-Tyne are examples of trip-wire systems (*15*).

2.4.1 Trip-wire Systems

Trip-wire systems focus on movement in only a specific location within the image field-of-view. These specific locations are called "detection zones." The rest of the image is ignored. Vehicles are detected when they pass through a detection zone. Movement is detected by the pixel intensity change within the detection zone. Vehicle presence is registered if the intensity change in the pixel is above a set threshold limit (*15*).

A trip-wire system can measure vehicle speed. Trip-wire systems determine speed in the same manner inductive loop detectors determine speed. Speed determinations require two detection zones at a known distance apart. Trip-wire systems calculate speed by knowing the distance between detectors and the time taken for a vehicle to cross the two detectors (*15*). Trip-wire systems have several advantages and disadvantages.

The advantages of trip-wire systems are (*15*):

- ♦ Trip-wire systems are able to operate in a multitude of directions
  The direction a group of pixels is heading is not important, only the pixel intensity changes within the detection zone.
- ♦ Vibrations are not detrimental
  Vibrations do not affect a trip-wire system as they do a tracking system. Slight movement of the detection zone does not create false detections, as long as the background image contrast does not change.
- ♦ Setup is generally easier
  Calibrating the camera and setting the variables are the only setup required.
- ♦ Limited processing power required
  Trip-wire systems limit the observation area to a small cluster of pixels necessary for vehicle detection.

The disadvantages of trip-wire systems are (*15*):

- ♦ Dependence on glare
  Trip-wire systems utilize reflections and shadows of vehicles for detection.
- ♦ Headlight association
  Most trip-wire systems utilize an algorithm to distinguish headlights significantly different from the algorithm used during the daytime hours.

2.4.2 Tracking Systems

The second type of video image processing system is classified as a "tracking" system. Tracking systems identify individual vehicles in an image and track the vehicles through that image. Sigru by Eliop, Titan by the Institute National de Recherché sur les Transports et leur Securite (INRETS), and Traffic Tracker by Sense and Vision Electronic Systems are examples of tracking systems (*15*). InVision by Intelligent Vision Systems, Inc. and The Mobilizer by Condition Monitoring Systems (CMS) are other examples of tracking systems (*18, 19, 20*).

Tracking systems determine the location of a vehicle from pixel intensity changes that occur from frame to frame in a video image. Moving vehicles are represented by groups or "*blobs*" of changing pixels. Tracking systems must associate these pixel groups and determine if the group is one vehicle or more than one vehicle. "*State Estimation*" and "*Data Association*" are two important processes in this determination. Vehicle state estimation determines which pixel groups in successive frames represent the same vehicle as the vehicle moves through the image. Tracking algorithms utilize a variety of filtering techniques to solve the problem of estimation. Data association is the process of choosing which pixel groups to use for vehicle state estimates. A tracking video image processing system must include an algorithm to determine if a pixel group is a separate vehicle. Tracking video image processing systems require the user to enter several parameters including: minimum distance between vehicles, minimum vehicle length and width, and maximum vehicle length and width (*15*). Tracking systems have several advantages and disadvantages.

The advantages of a tracking system are (*15*):

- Ability to handle shadows
  Tracking systems utilize vehicle width measurements to distinguish shadows from vehicles.
- Ability to handle lane changes
  Tracking systems are able to track the vehicle through the zone until it leaves the zone.
- Ability to associate headlights with vehicles
  Tracking systems associate many blobs for one vehicle. The blobs caused by a vehicles headlights require only a slight modification of the daytime algorithm.
- Less sensitive to noise
  Tracking systems ignore noise since all vehicles must have a minimum size requirement.

The disadvantages of tracking systems are (*15*):

- The number of variable input requirements
  Tracking systems analyze pixel changes for a vehicle throughout the field-of-view. Vehicle parameters, such as vehicle length and width, are required for the system to set some threshold intensity of the many blobs associated with a moving vehicle.
- "Blobifying" on aerodynamic cars
  Tracking systems rely on distinguishing the edges of a vehicle to track the vehicle. Aerodynamic vehicles sometimes avoid reflections and create gradual changes in intensity.
- Sensitive to vibrations
  The images appear to be moving erratically when the camera is vibrating.
- Significant processing power required for image processing
  Tracking systems must accomplish many computation intensive tasks in real-time to detect movement.

An advantage that both types of video image processing systems have over competing detection systems is their flexibility and ability to detect traffic in multiple locations within the camera's field-of-view. The detection zones do not physically exist on the pavement, allowing detection zones to be removed or adjusted to improve detection. Additionally, a single camera can replace many loops, thereby becoming cost-effective (*3, 21*).

2.4.3 Phenomena Affecting Video Image Processing Systems

Phenomena which can compromise the accuracy of video image processing systems include: reflections, shadows, occlusion, darkness, and transitional lighting. Reflections can be useful in detecting vehicles, especially in poor illumination, because they can enhance the contrast between the object and the background. However, reflections also have a negative side. Especially at night or on wet pavement, reflections can trigger changes in a pixel's value resulting in erroneous detection as a moving vehicle. Most video image processing systems utilize a nighttime detection algorithm to minimize these problems (*15*).

Shadows, like reflections, are both useful and detrimental. Useful shadows exist under and to the side of a vehicle on bright days. Small, dark shadows beneath a moving vehicle provide increased contrast between the vehicle and the road surface, making the vehicle easier to detect. Long vehicular shadows extending across more than one lane of traffic pose a disadvantage. Slow moving shadows from tall stationary objects, such as luminaries or traffic signal poles, are also difficult to interpret. Changing shadows are problematic for both trip-wire and vehicle tracking systems (*15*).

Nighttime conditions affect video imaging systems. In some situations, vehicle detection at night is easier than during daylight due to greater contrast by vehicles' headlights. However, the reflection effects of headlights need further attention to avoid double counting. Either dawn or dusk transitional lighting causes problems for video image processing systems. Some systems utilize two separate detection schemes, one for daytime and another for night, to process the video image. Transitional lighting can confuse the system, partly because some headlights are on and some are off. (*15*).

Occlusion occurs when one or more vehicles obstruct the view of another vehicle. Occlusion has a major impact on detection when one vehicle "hides" any horizontal edge of another vehicle, thus giving the appearance of one larger vehicle. Vehicles can occlude vehicles in other lanes or in the same lane. Occlusion can occur in trip-wire and tracking systems. The most practical solution to overcome occlusion is improved camera position (*15*).

2.5 COMPARISON BETWEEN VIDEO IMAGE PROCESSING DETECTION AND INDUCTIVE LOOP DETECTION SYSTEMS

The need for more reliable real-time traffic information is increasing. Installation and maintenance costs of present detection methods, especially installations in the pavement, have risen. Alternative detection methods are being examined with the objective of reducing installation and maintenance costs. One study estimated that a fully instrumented intersection using video image processing would cost less than the same intersection implemented with inductive loop detectors (*13*, *14*).

Michalopoulos, the developer of AutoScope, (*22*) et al., compared the economics between inductive loop detectors and the AutoScope machine-vision video image processing system. The study was performed on a section of IH-36 north of St. Paul, Minnesota. The study showed benefit-cost ratios from 1.25 to 18.4 with most of the cost savings due to substantially reduced road-user delay cost. The direct cost of inductive loop installation, in most cases, is less than the AutoScope installation cost. The inclusion of road-user cost (e.g., motorist delay and excess fuel consumption) caused the comparative cost of inductive loops to be greater than video detection in three scenarios of implementation. Additional video detector savings occur during road surface rehabilitation if loops require replacement. In that case, video does not require replacement. Costs of direct video image processing detection methods should decline as production levels increase. However, for simple isolated traffic measurements, inductive loops may remain cost effective.

MacCarley (*23, 24*) et al., evaluated the ability of video image processing systems to count vehicles and determine vehicle speeds. Cameras were placed to the side and along the centerline of several freeway overpasses in the Los Angeles area. Twenty-eight test conditions were analyzed with camera heights ranging from 8.2 m to 14 m (27 ft. to 46 ft.) Test conditions included: ideal daylight conditions, inclement weather conditions, non-optimum camera placement, daylight to nighttime transition lighting conditions, vehicle shadows, and congested traffic conditions. The study involved both trip-wire and tracking systems. Overall error rates of less than 20 percent were observed over a mixture of traffic flow densities and optimal weather conditions and camera placement. Under optimum daylight conditions, trip-wire type systems counted vehicles more accurately and tracking type systems measured vehicle speeds more accurately. Under less than ideal conditions, the performance of both system types degenerated. Changes in light levels at sunrise and sunset and inclement weather reduced the detection accuracy of all of the systems (*23, 24*).

Another study by Michalopoulos (*3,21, 25*) et al., evaluated the AutoScope video image processing system in a freeway application. Several cameras were placed at two sites on a Minneapolis freeway. At one site, cameras were placed at a height of 13.7 m (45 ft.) and 9.1 m (30 ft.) from the edge of the pavement. These tests identified several problems with the AutoScope system. One problem involved headlight reflections at night on wet pavement. A set of night parameters was implemented and reduced the false detection rate from 30 percent to 7 percent. Other problems identified by this study included: vehicle shadows, light transitions, occlusion, wind, and sun reflections. Adjustments to the AutoScope system decreased the false alarm rate and the results closely matched inductive loop data.

2.6 VEHICLE SPEED CALCULATION OF VIDEO IMAGE PROCESSING SYSTEMS

Vehicle speeds determined by video image processing systems are usually higher than actual vehicle speeds. A bias in the speed calculation results from calibrating the field-of-view on a plane along the roadway surface. However, the video image processing system tracks the vehicle on a plane closer to the camera. A video image processing system may lock onto a vehicle's hood or rooftop while tracking the vehicle through the field-of-view (*26*). The increased speed calculated by the video image processing system is proportional to h_{VS}/h_C, where h_{VS} is the vehicle signature, or vehicle height, and h_C is the camera height. Figure 2-2 illustrates this phenomenon, where d_{ACTUAL} is the actual distance the vehicle signature traverses through the detection zone and $d_{CALIBRATED}$ is the distance determined by the calibration of the image (*27*, *28*). A speed calculation adjustment factor is obtained by the following equation.

When:

$$CAL_{adj} = \frac{h_C}{h_C + h_{VSest}}$$

CAL_{adj}	=	vehicle speed calculation adjustment factor
h_C	=	camera height
h_{VSest}	=	estimated vehicle signature

The vehicle speed generated by the video image processing system, multiplied by the calculated adjustment factor, yields the adjusted vehicle speed.

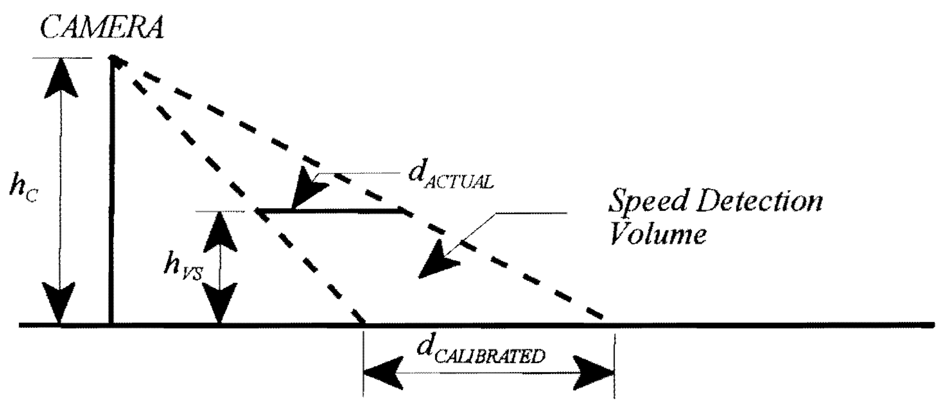

FIGURE 2-2. Video Image Processing System's Speed Detection Volume.

Another source of speed error variability is the processing speed of the video image processing system. The processing speed is in accordance with the United States' video processing standard of thirty (30) frames per second. The frame processing rate results in some uncertainty in the recorded event time relative to the true event time (*28*).

2.7 VIDEO CAMERA CONSIDERATIONS

The camera field-of-view is the area seen by the camera. This area will vary depending upon the height a camera is mounted and the camera type. Cameras have imagers varying from 8.4 mm (1/3 in.) to 25.4 mm (1 in.) The focal length is the distance from the imager to the lens.

The field-of-view decreases as the focal length increases. The combination of imager size and focal length gives the field-of-view.

The horizontal angle-of-view is calculated from the focal length and imager size. Half of the imager's width is divided by the focal length. The inverse tangent of this factor gives half of the horizontal angle-of-view. Doubling this angle gives the total horizontal angle-of-view. The vertical angle-of-view is 75 percent of the horizontal angle-of-view. These angles remain constant given a focal length and an imager size. A list of camera angles-of-view is available from most camera manufacturers. These angles are used to calculate a camera's field-of-view.

See Figures 2-3 and 2-4 to reference the following calculations. The vertical angle from the camera to the first point of interest, angle a_1, is related to the camera height (h) and the horizontal distance to the first point of interest (x_1) in the following formula:

$$a_1 = \mathrm{Tan}^{-1}(x_1/h)$$

The summations of angle a_1 and the vertical angle-of-view (V_{aov}) give angle a_2. This angle was used in calculating the distance to the farthest visible point (x_2). These formulae calculate the value of x_2:

$$a_2 = a_1 + V_{aov} \qquad\qquad x_2 = h(\mathrm{Tan}(a_2))a_2$$

Before finding the horizontal field-of-view, the Pythagorean theorem was used to calculate the hypotenuse (z). Distance z_1 gives the distance from the elevated camera to the ground at point x_1. Distance z_2 gives the distance from the elevated camera to the ground at point x_2.

$$(z_1)^2 = (x_1)^2 + (h)^2 \qquad\qquad (z_2)^2 = (x_2)^2 + (h)^2$$

(The hypotenuse can also be found by multiplying the cosine of each vertical angle (a_1 and a_2) by the camera height.)

The horizontal angle-of-view (H_{aov}) must now be used in combination with the hypotenuse to determine the width of the field-of-view at points along the ground. Using the hypotenuse (z_1) to the closest visible point x_1, the horizontal field-of-view (w_1) was calculated. Using the hypotenuse (z_2) to the farthest visible point (x_2), the width of the field-of-view (w_2) at point x_2 was calculated. The following formulae were used for these calculations:

$$w_1 = 2z_1(\tan(H_{aov}/2)) \qquad\qquad w_2 = 2z_2(\tan(H_{aov}/2))$$

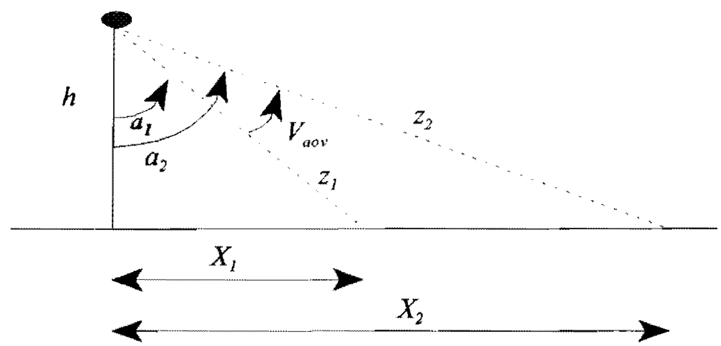

FIGURE 2-3. Camera Angle-of-View (side view)

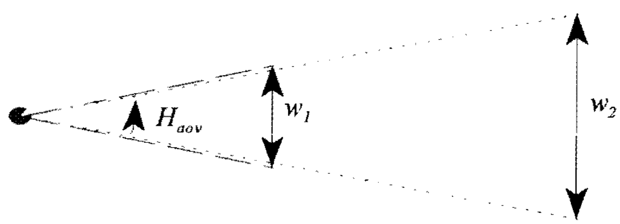

FIGURE 2-4. Camera Angle-of-View (planar view)

2.7.1 Field-of-View Calculations

The plan view in Figure 2-5 shows the fields-of-view for a 12.7 mm (½ in.) imager using 6 mm, 8 mm, 10 mm, 12 mm, and 25 mm focal length cameras. Since the focal length, imager size (aperture), and heights of the cameras were known, these fields-of-views were calculated in Appendix Tables A-1 through A-8 using the Burle Technologies Inc. Field-of-View Guide and the above formulas. Each camera's field-of-view represents the area that can be seen when the camera is positioned 9.1 m (30 ft.) high and the distance (on the ground) between the camera and the first point of interest (x_1) measures 24.4 m (80 ft.) All of the camera fields-of-view shown on the plan view extend into the horizon, except for the 25 mm camera.

2.7.2 Field-of-View As Determined by Computer Software

The three-dimensional view in Figure 2-6 was generated on AutoCAD Release 13 and overlooks a basic six lane road that has utility poles along one side. This shows the view from a 6 mm camera when placed 9.1 m (30 ft.) above the ground and 24.4 m (80 ft.) behind the stop line. From this camera's location, the field-of-view extends above the horizon. This

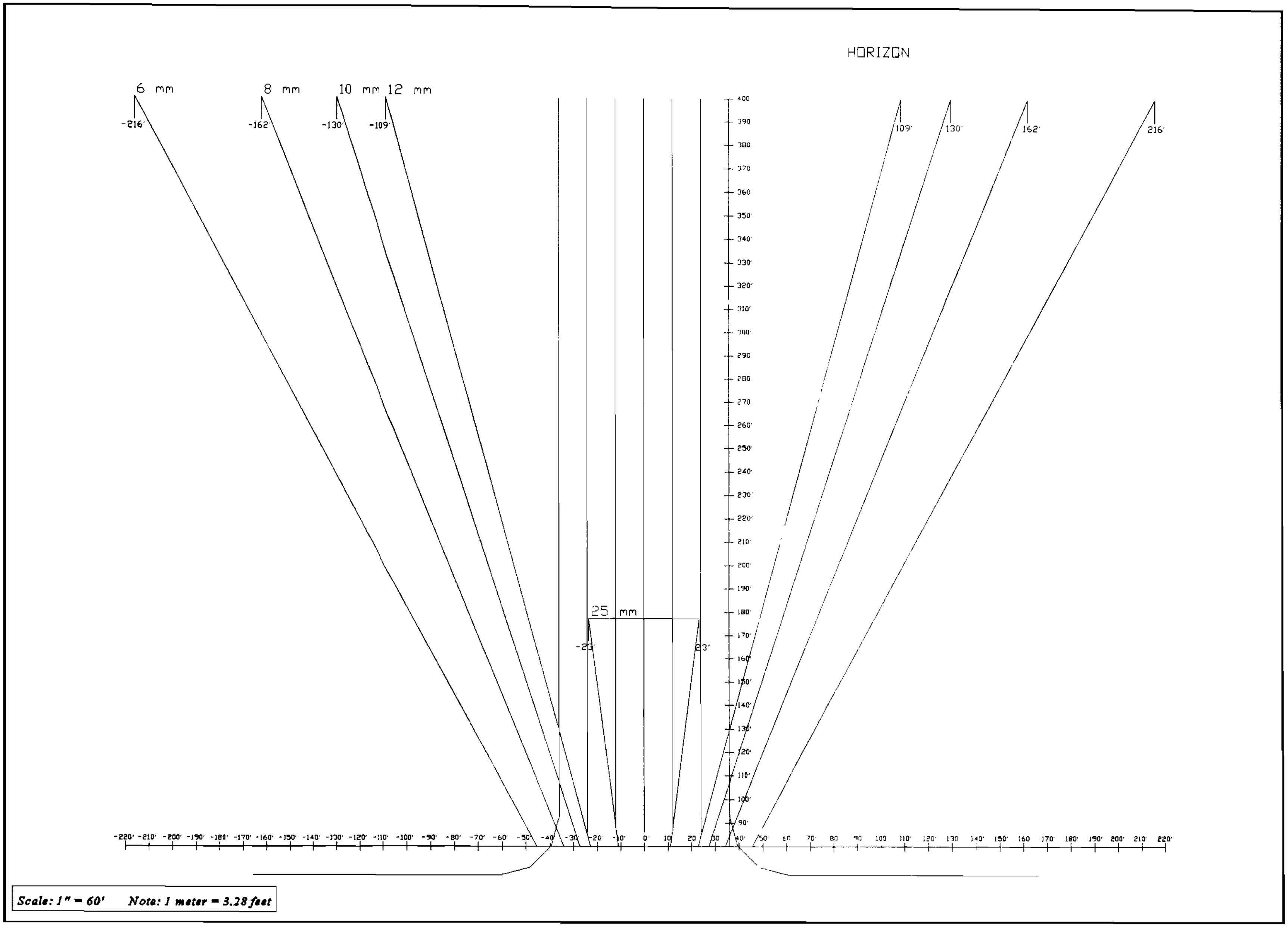

FIGURE 2-5. Field-of-view for Different Cameras at 9.1 m (30 ft.) Height

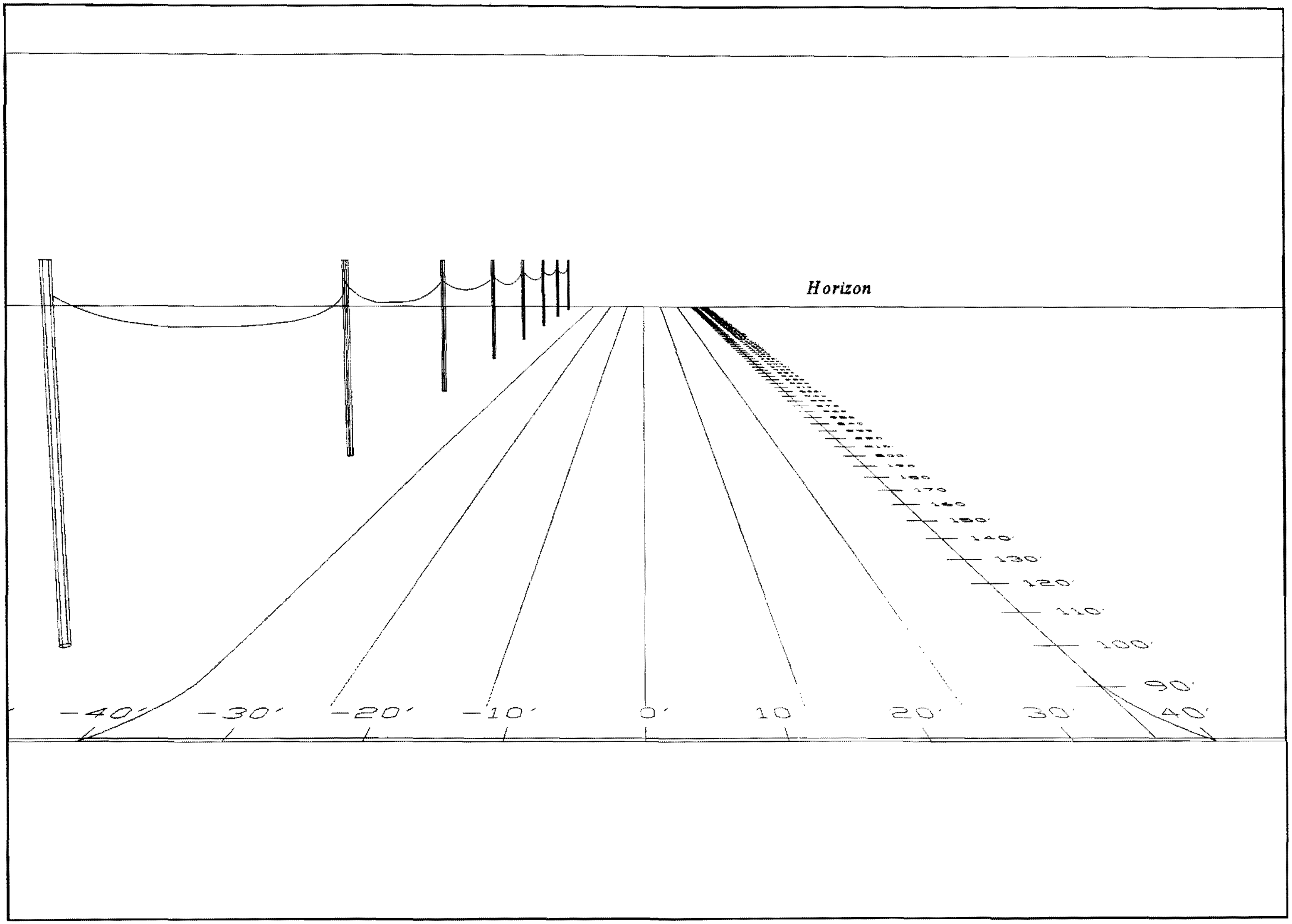

FIGURE 2-6. Three-Dimensional View with a 6 mm Camera at 24.4 m (80 ft.) from the Stop Bar and 9.1 m (30 ft.) High

figure is intended to show the utility of using computer software to determine a preliminary camera position, thus reducing valuable field installation and design time. The software program, Microstation, later became the primary instrument for this purpose simply because TxDOT uses it on a widespread basis and because it offers an aspect ratio that replicates that of a CCD camera. Using Microstation, a video system designer can closely replicate the view from the camera at any location, if appropriate site specific features are known.

Features that challenge designers, perhaps compromising the accuracy of video systems, may include: locations of existing camera supports, sight obstructions, roadway geometric features, and high speeds on intersection approaches. These features may require specific camera focal lengths, mounting heights, and/or offsets to yield optimum results. Without a technique to assist in locating cameras, especially in tight urban environments, designers may be forced to use trial-and-error methods.

2.7.3 Instructions for Microstation Three-Dimensional Utility

In order to facilitate the use of the Three Dimensional (3-D) feature of Microstation, the following brief instructions, supplemented by a computer file of some typical roadways, can be used to replicate actual roadway situations. When the given drawing is opened, there should be two views: View 1-Top, which is an overview of the intersection, and View 4, which is the camera view. (NOTE: Do not change the size of the View 4 window! This will alter the aspect ratio of the 3D view.) The camera has already been set at a specific coordinate position.

To find the coordinates of the camera:

1) Click on 'Element' on the toolbar
2) Select 'Information'
3) Click on the circle in View 1 located to the bottom left of the intersection
4) Information about this circle will appear on the screen
   - The circle's center are the x- and y- coordinates of the camera
   - Write down these coordinates for future reference
   - The z-coordinate was designated to be 40 when the camera was set

To change the camera position:

1) Click on 'View' on the toolbar
2) Select 'Camera'
3) Select 'Move Camera'
4) A 'Select View' prompt will appear. Click anywhere in View 4 to select it as the view to move the camera in
5) At the 'uSTN>' prompt, type 'xy=x,y,z' filling in the x,y, and z values of the camera coordinates
   Ex: If the x- and y-coordinates of the camera were found to be 45,60,

to move the camera to a 9.1 m (30ft.) height, enter xy=45,60,30

6) A 'Define the Front Clipping Plane' prompt will appear. Click on any point below the circle in View 1

7) A 'Define the Back Clipping Plane' prompt will appear. Click on any point at the top of View 1 that is above the drawing

To change the position of the camera's target:

1) Click on 'View' on the toolbar
2) Select 'Camera'
3) Select 'Move Target'
4) A 'Select View' prompt will appear. Click anywhere in View 4 to select it as the view to move the target in
5) At the 'uSTN>' prompt, type 'xy=x,y' filling in the x and y values of the new target position. To determine which coordinates to use, add offset distances to the x- and y-coordinates of the camera's position.
   Ex: If the camera's coordinates are 45,60, and the camera should be pointed 12.2 m (40 ft.) to the right and 15.2 m (50 ft.) ahead, enter xy=85,110
6) A 'Define the Front Clipping Plane' prompt will appear. Click on any point below the circle in View 1
7) A 'Define the Back Clipping Plane' prompt will appear. Click on any point at the top of View 1 that is above the drawing

To change the camera's focal length:

1) Click on 'View' on the toolbar
2) Select 'Camera'
3) Select 'Lens'
4) A box will appear. Make sure View 4 is selected
   - -Change the focal angle according to the CCTV angles for the desired focal length (ie. a 6 mm camera has a focal angle of 56.1)
   - -Hit the tab button to get the Microstation focal length to correspond to the focal length that was entered
   - -Click on 'Apply'

To save View 4 as a Word Perfect Graphics file:

1) Click on 'File' on the toolbar
2) Select 'Save Image As...'
3) Choose the following information in the box that appears:
   View: 4
   Format: WordPerfect (WPG)
   Mode: 256 Colors
   Shading: Smooth
   Shading Type: Anti-alias
   Resolution: x:1200 y:758

Gamma Correction: 1.00

4) Click on 'Save'

Based on this procedure, research staff developed Figures 2-7 to 2-12 for signalized intersections and other views not shown to demonstrate the use of the 3-D feature of Microstation. These figures show only camera heights of 12.2 m (40 ft.), although users can readily plot views based on other camera heights, offsets, and focal lengths using this procedure and the Microstation software. The camera is offset 1.5 m (5 ft.) from the outside lane edge in all cases, through and left turn lane widths are 3.4 m (11 ft.), and all imagers are 12.7 mm (½ in.) Intersections shown are all symmetrical; for example, the "4x4" intersection has two through-lanes in each direction on each of the four legs. The "4x4" intersection has one left turn lane; whereas the "6x6" and "8x8" intersections have two left turn lanes each. Each view shows 30.5 m (100 ft.) "tick" marks along the right side of the monitored approach. In all cases the Camera parameters corresponding to these and other views are tabulated in Section 6.2.4 Implementation Recommendations.

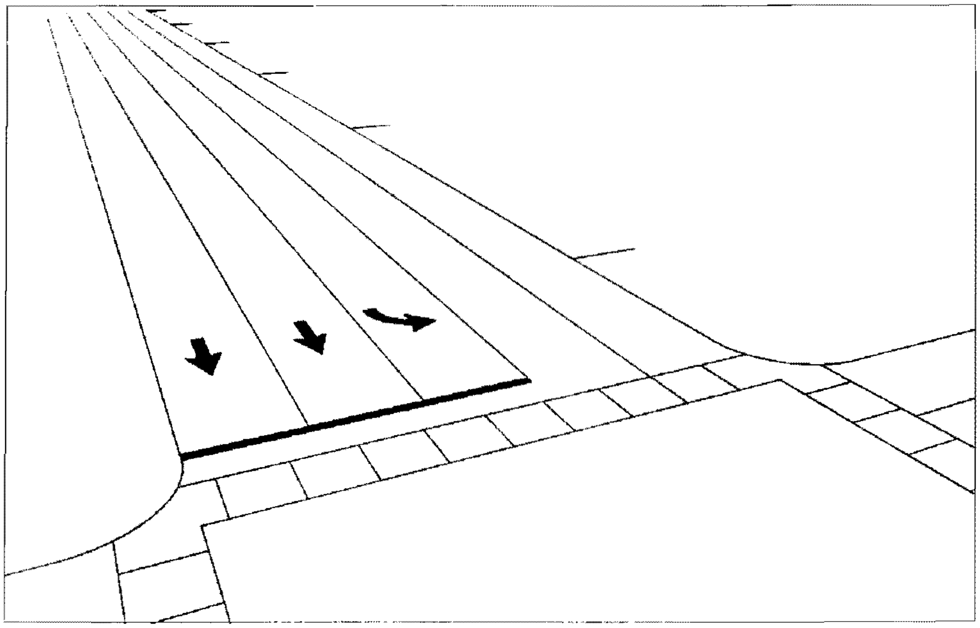

Figure 2-7. 4x4 Intersection - 6 mm Camera at 12.2 m (40 ft.)Height

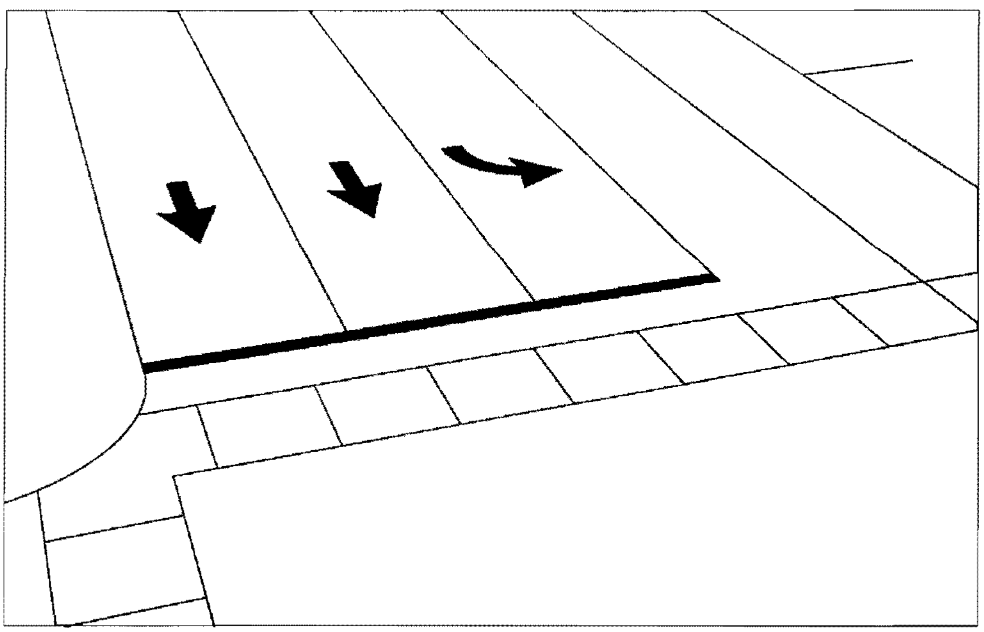

Figure 2-8. 4x4 Intersection - 10 mm Camera at 12.2 m (40 ft.) Height

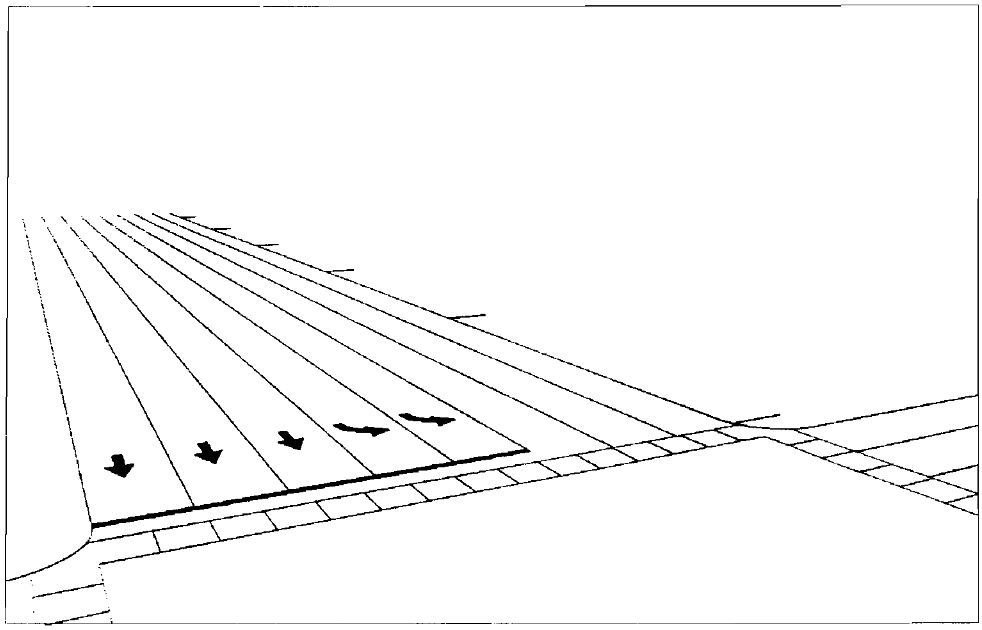

Figure 2-9. 6x6 Intersection - 6 mm Camera at 12.2 m (40 ft.) Height

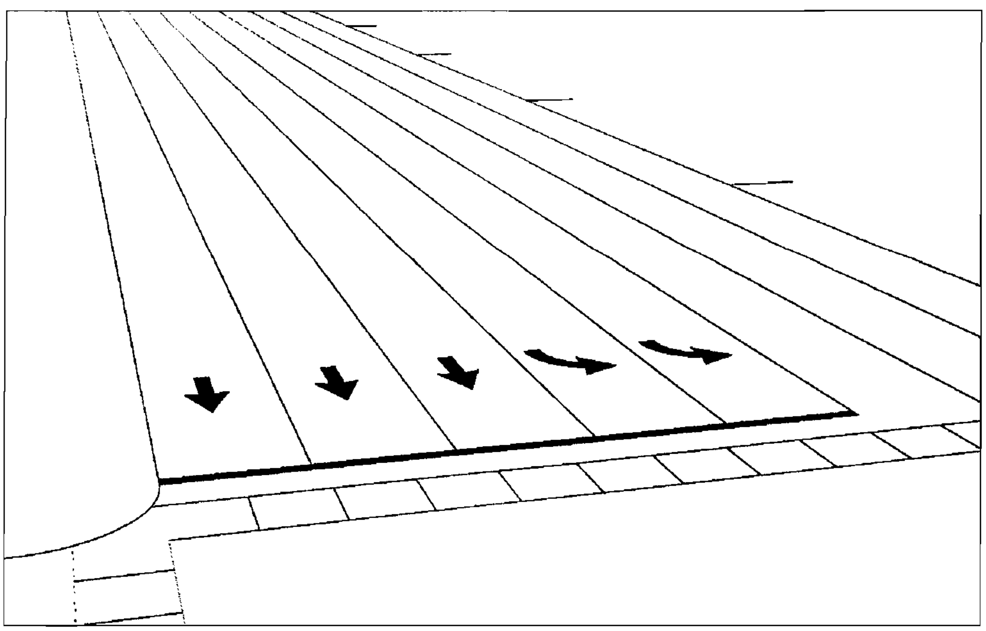

Figure 2-10. 6x6 Intersection - 10 mm Camera at 12.2 m (40 ft.) Height

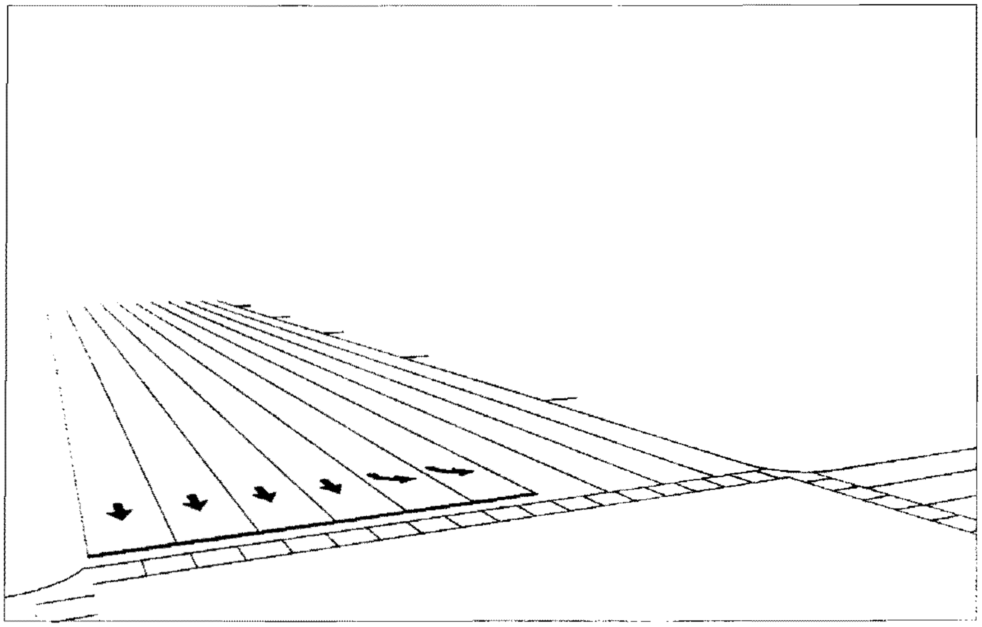

Figure 2-11. 8x8 Intersection - 6 mm Camera at 12.2 m (40 ft.) Height

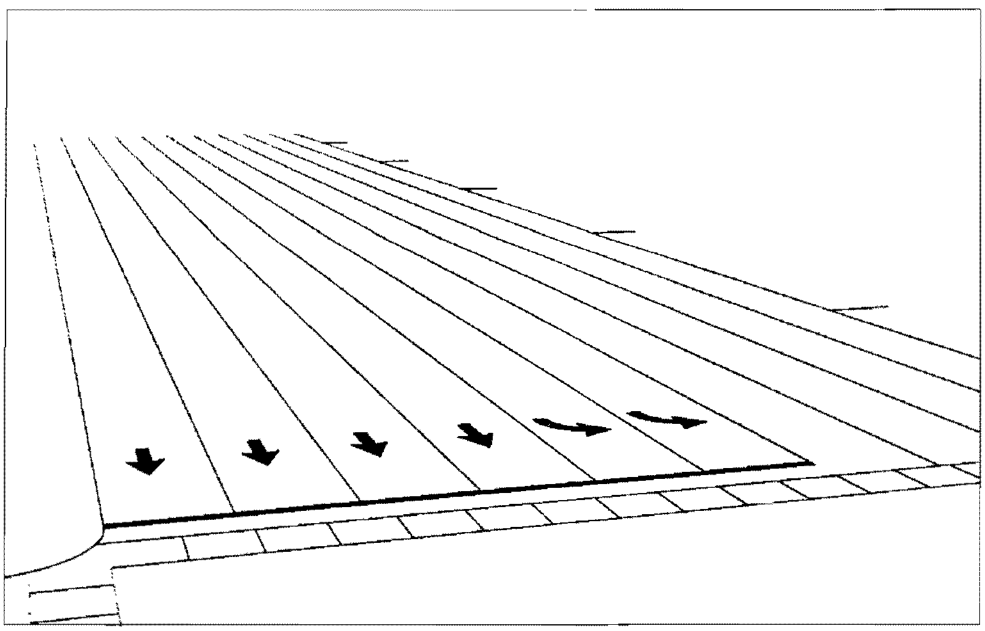

Figure 2-12. 8x8 Intersection - 10 mm Camera at 12.2 m (40 ft.) Height

3.0 METHODOLOGY

This chapter describes the methodology used in this study. The study site, video image processing system, equipment, various study parameters, and the types of tests conducted are described.

3.1 STUDY SITE

The study site that was selected for this research was the Highway Safety Research Center Proving Grounds located at the Texas A&M University Riverside Campus, Bryan, Texas. The Riverside Campus is a former Air Force base which hosts a large expanse of concrete runways and parking aprons. It is ideally suited for experimental research and testing and is used as a test site for numerous types of research. Runway 35C was used as the location for all testing for this study and provided a controlled field laboratory testing environment.

The video image processing system used in this study required an alternating current (AC) power source. Electric power to operate the system during testing was provided by a gasoline powered generator. A 15.2 m (50 ft.) trailer-mounted tower was used to support the camera at the heights tested in this research study. A cable and pulley system was used to hoist the camera mounting apparatus to the required camera height.

3.2 VIDEO IMAGE PROCESSING SYSTEM

The video image processing system used for all of the tests is the Autoscope™ 2004 system by Image Sensing Systems. Autoscope™ is classified as a trip-wire system. A 386 DOS based personal computer served as the "supervisor" computer. The Autoscope™ software was loaded on the supervisor computer and was used to create the detector files. The camera imaging device used was a 12.7 mm (½ in.) interline transfer microlens Charged Coupled Device (CCD). The camera lens was a 6 mm, f1.2 auto iris lens.Autoscope™

3.3 STUDY PARAMETERS

Proper camera placement is critical to the successful performance of a video image processing system. A properly placed camera accurately detects vehicles, provides critical information for transportation management agencies, maximizes the video image systems's capabilities, and minimizes the system's cost. The tests performed in this study identified the video image processing system's range in accurately distinguishing the number of vehicles passing through the camera's field-of-view. The detection range is a function of the camera placement and the camera's field-of-view.

3.3.1 Camera Field-of-View

The camera's field-of-view is the area most clearly seen through the lens on the camera. The field-of-view is a function of the camera height, camera vertical angle, camera placement relative to the travel lanes, camera orientation with respect to traffic direction, and the camera lens focal length. The field-of-view must include the area of detection.

3.3.2 Project Study Area

The project study area or area of detection is defined by the roadway width and the farthest distance from the camera where detection is first achievable. Figure 3-1 illustrates the study area. The roadway width selected for this research project was 25.6 m (84 ft.) This width corresponds to one direction of a ten-lane freeway. The cross-section consisted of 1.5 to 3.7 m (5 to 12 ft.) travel lanes, a full 3.7 m (12 ft.) right shoulder, and a 3.7 m (12 ft.) left (median) shoulder. Runway 35C, the study site at Texas A&M University's Riverside Campus, has longitudinal construction joints every 3.8 m (12.5 ft.) These longitudinal construction joints were used as the lane lines for this study. Therefore, the actual roadway width used in this study was 26.7 m (87.5 ft.) The actual cross-section consisted of five 3.8 m (12.5 ft.) travel lanes, a 3.8 m (12.5 ft.) right shoulder; and a 3.8 m (12.5 ft.) left or median shoulder.

The distance from the camera to the farthest detection point for these tests was 121.9 m (400 ft.) upstream from the camera tower. This distance was determined by the capability of the camera lens available for these tests. The camera lens focal length is fixed at 6 mm. This lens provides a viewing distance of 121.9 m (400 ft.) upstream of the camera tower to 12.2 m (40 ft.) from the camera tower. Each lane was designated by a number. Table 3-1 identifies each lane number and its corresponding location. Lanes 1 through 5 correspond to five freeway lanes with a camera offset of 5.3 m (17.5 ft.) Lanes 2 through 6 correspond to a five lane freeway with a camera offset of 9.1 m (30.0 ft.)

TABLE 3-1. Lane Designation Location

Lane Number	Lane Location with Respect to Camera Location
1	5.3 m (17.5 ft.) offset
2	9.1 m (30.0 ft.) offset
3	13 m (42.5 ft.) offset
4	16.8 m (55.0 ft.) offset
5	17.5 m (67.5 ft.) offset
6	24.4 m (80.0 ft.) offset

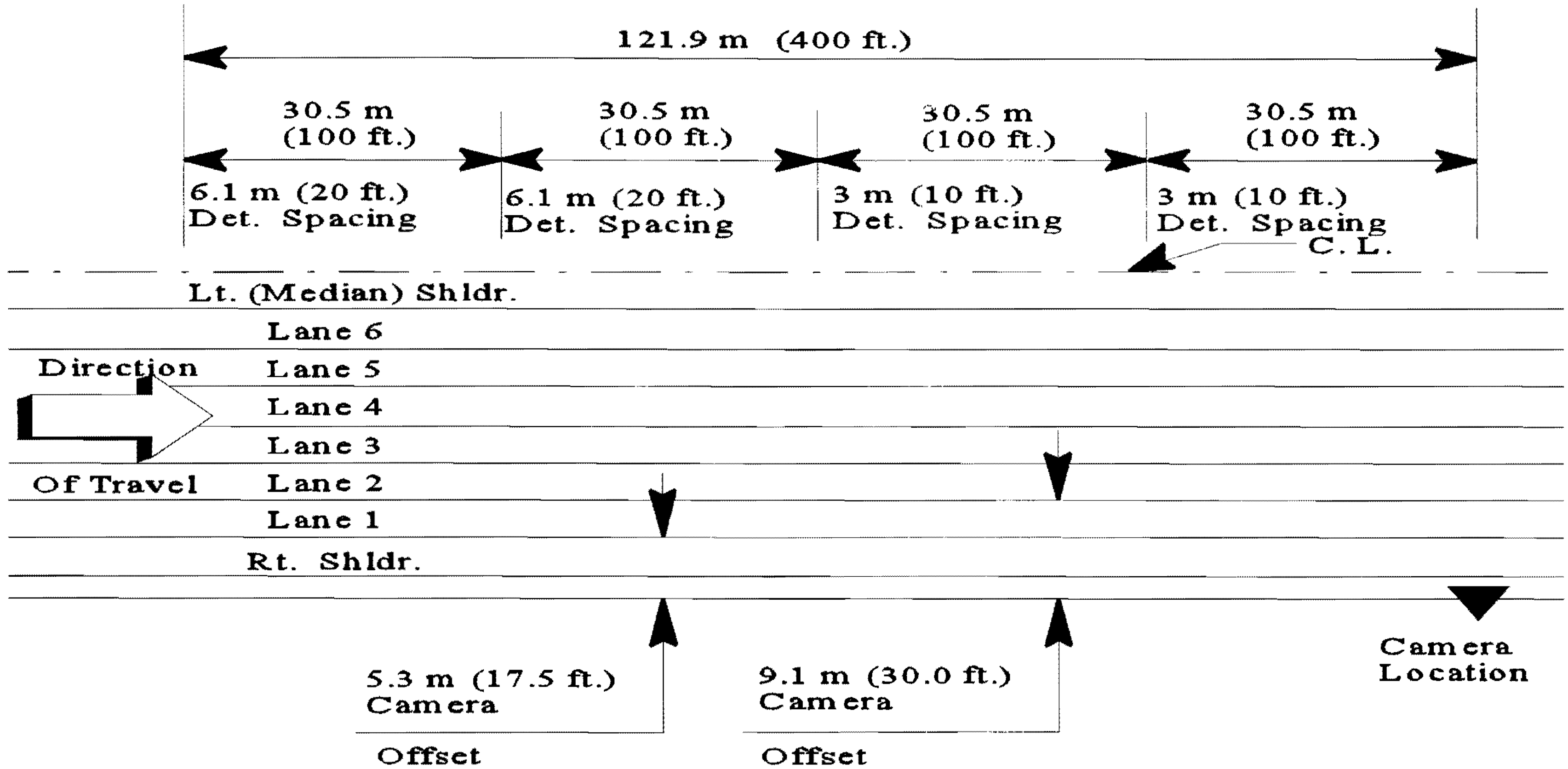

FIGURE 3-1. Project Study Area

3.3.3 Camera Height

Camera height is a component of the camera's field-of-view. The camera height, along with the outer detection area limit, determines the vertical angle of the camera so the detection area or project study area is within the field-of-view. The tests performed in this study use three camera mounting heights. The camera heights were: 9.1 m (30 ft.), 12.2 m (40 ft.), and 15.2 m (50 ft.)

3.3.4 Camera Location

The camera can be placed in a variety of locations. The three primary locations are in the median, directly over the travel lanes, or to the right of the travel lanes. The camera position for the test conditions in this study is to the right of the travel lanes, outside the right shoulder. Two camera offset distances were analyzed in this study. The first offset distance of 9.1 m (30.0 ft.) represents a camera location away from the travel lanes and corresponds to the Texas Department of Transportation's (TxDOT) and the American Association of State Highway and Transportation Officials's (AASHTO) horizontal clear zone design guideline (*29, 30*). The second offset distance of 5.3 m (17.5 ft.) represents a camera location near the edge of the travel lanes and corresponds to the approximate location of a sign support structure. In this case, 1.5 m (5 ft.) radar from the edge of the pavement. The camera offset position, with the roadway width desired to be covered, determines the horizontal angle of the camera so detection area is within the field-of-view.

3.3.5 Vehicle Speed

Video image processing systems are able to determine vehicle speeds. Autoscope™, a trip-wire system, utilizes "speed-traps" to determine vehicle speeds. A speed trap is created in conjunction with a counter detector. A "speed-trap" detector file is created using AutoScope™ to determine the vehicle speeds using Autoscope™. "Speed-trap" detectors were set 30.5 m (100 ft.) and 91.4 m (300 ft.) upstream of the camera. "Speed-trap" detectors were placed in lanes 1, 2, 4, 5 and 6. The vehicle speeds determined by Autoscope™ were compared with the speeds determined by a radar speed gun. The radar speed gun used during the entire testing period was a Kustom Electronics "Roadrunner" hand held detection unit. This unit is not "detuned" to prevent detection by radar detection systems. During testing, the radar speed gun operator was located in the adjacent travel lane when the speed readings were taken. This location minimized the reflection angle. Three vehicle speeds were used for all of the tests performed in this study. These vehicle speeds were: 32 km/h (20 mph), 72 km/h (45 mph), and 88 km/h (55 mph.)

3.3.6 Weather Conditions

Weather conditions can affect the accuracy of video image processing systems. Testing in this study used only dry, clear weather conditions. These conditions minimized the effects weather has on the effectiveness of the video image processing system. Additional tests were planned for inclement weather; an extremely dry spring and summer in 1996 did not produce the needed conditions at time periods when personnel and equipment were available.

3.3.7 Light Conditions

Light conditions can also affect the effectiveness of video image processing systems. The majority of testing occurred during midday hours between 10:00 a.m. and 4:00 p.m. Central Daylight Savings time. Midday conditions minimize the effects of long shadows. Limited testing also occurred during non-midday hours as described later.

3.3.8 Wind Conditions

Wind affects the amount of sway on the camera mounting system. Sway was not included as a variable in this study; therefore, the test set-up intentionally minimized sway. Researchers attached guy wires to the camera mounting apparatus to keep it stationary. Securing the camera mounting apparatus and testing only in calm to light wind conditions minimized the wind's affect on camera sway.

3.3.9 Vehicle Headway

For all tests, the spacing between vehicles corresponded to a 1.5 second headway. This headway corresponds to the mean headway for a freeway capacity of 2400 passenger cars per hour per lane (pcphpl) (*31, 32, 33, 34*). Figure 3-2 illustrates the relationship of the two vehicles in determining the gap distance. The vehicle length for passenger car tests was a constant 5.5 meters (18 ft.) The gap distance is a function of vehicle speed. The equation for determining the gap distance between vehicles is:

Gap Dist = [veh. spd. (mph) *x* (5280/3600) *x* headway] - veh. length

Table 3-2 lists the distance between the two vehicles for the given speed. The gap distance between vehicles is maintained by towing the second vehicle using a 9.53 mm (3/8 in.) steel cable.

TABLE 3-2. Gap Distance Between Vehicles

Vehicle Speed km/h (mph)	Gap Distance m (ft.)
32 (20)	7.9 (26)
72 (45)	24.7(81)
88 (55)	31.4 (103)

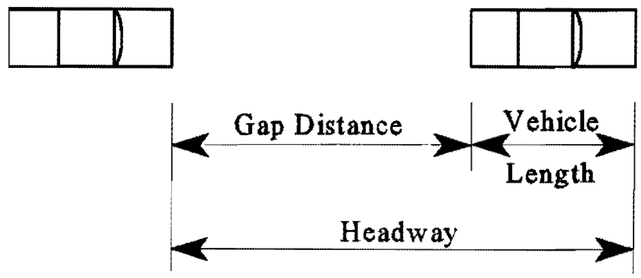

FIGURE 3-2. Gap Distance Between Vehicles

3.3.10 Vehicle Type

Test vehicles for car tests were two 1991 and two 1992 Chevrolet Impalas. Each vehicle measured 5.5 m (18 ft.) in length from front bumper to rear bumper. The color of all four passenger cars was white. The height of each vehicle from the ground to the roof was estimated at 16.4 m (5 ft.)

3.4 DATA COLLECTION

3.4.1 Sample Size Determination

The Autoscope™ software's detector placement accuracy and precision determined the number of vehicle pair test runs in each travel lane. Software limitations prohibited detector placement closer than 6.1 m (20 ft.) intervals at distances greater than 61 m (200 ft.) upstream from the camera position. This software limitation is due to the minimum number of pixels required for a detector (2 pixels) and the detector location relative to the camera location. The distance width of each pixel increases as the detector location increases from the camera position. The following equation yielded the sample size (*35*):

$$n = \left| \frac{z_{\alpha/2}\sigma}{d} \right|^2$$

where:

n = sample size

$z_{\alpha/2}$ = critical normal deviate for specified reliability 1 - α
1.96 for 95% confidence level

σ = population standard deviation of data

d = desired precision

Using a desired precision, d, of 20 and a standard deviation of 30, obtained from previous data, the required sample size was calculated as:

$$n = \left[\frac{(1.96)(30)}{20}\right]^2$$

$$n = 8.6 \text{ runs per travel lane}$$

Researchers ran each vehicle configuration 10 times in each travel lane to satisfy the minimum sample size requirements.

3.4.2 Types of Tests Conducted

The majority of tests occurred during midday hours when shadows were not a significant problem. Both midday and non-midday tests were conducted in two series using passenger car pairs. In the first series, two passenger car pairs travel in alternating travel lanes beginning with the right most travel lane. A passenger car pair consisted of one passenger car behind another passenger car. The distance between the two cars is as shown in Table 3-2 for the given test speed. The two vehicle pairs traveled in lanes 1 and 4 during the first set of test runs and in lanes 2 and 6 during the second set of test runs. Lane 1 and 4 then lane 2 and 6 lane pairings were chosen to eliminate influences of the other vehicle pair on the detectors.

The second series of tests studied interference from vehicles in adjacent travel lanes. Two two-car pairs were used during this testing phase. The two two-car pairs traveled in travel lanes 5 and 6. The lead car of the travel lane 6 vehicle pair was positioned between the left rear wheel and the rear bumper of the lead car of the travel lane 5 vehicle pair. Comparing travel lane 6 vehicle detection location data from lane group 2-6 test runs to travel lane 6 vehicle detection location data from lane group 5-6 determines if passenger cars in adjacent travel lanes influence the detection ability of the video image processing system. Figure 3-3 illustrates the lane group 5 - 6 test configuration.

Non-midday tests followed similar procedures as described above, but the more limited amount of data provided less conclusive evidence of results. There were fewer lanes used for each speed and camera height, but there were at least 10 runs for each set of selected conditions, with the intent of allowing statistical analysis. Testing occurred both with and without headlights and on both wet and dry pavement. Wet pavement testing only occurred in selected lanes and only under full darkness, with water provided by a water truck at the site.

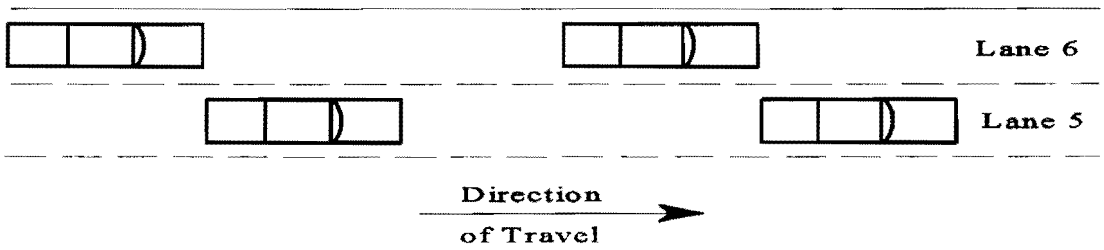

FIGURE 3-3. Lane Group 5-6 Test Configuration

The initial series of non-midday tests investigated the accuracy of Autoscope™ detection during darkness. Pairs of cars traveled in lanes 1 and 4, lanes 2 and 6, and a staggered two car pair ran in lanes 5 and 6. The camera height was 12.2 m (40 ft.) throughout the night tests that used cars only. The cars operated with headlights on and maintained constant headways and a constant speed of 32 km/h (20 mph).

The second series of non-midday tests utilized a different location to test the video system's susceptibility to glare or other problems when facing the sun. The test procedures and car positioning were the same as in the previous test series; speeds were constant at 32 km/h (20 mph). The camera height was 9.1 m (30 ft.), the camera offset (from lane 1) was 9.1 m (30 ft.), and camera placement replicated the previous lane configuration to minimize the number of variables. During these tests, lane 1 replaced lane 2 from previous test, and lane 3 replaced lane 4, and so on. These sunrise tests used lanes 1 and 3, and an occlusion test for two pairs of cars in lanes 4 and 5. This simulates lanes 2 and 4, and an occlusion test in lanes 5 and 6 from previous tests. Some tests used headlights on; others used no headlights.

The third series of non-midday tests investigated occlusion by using a single-unit box truck and three cars. The test location returned to Runway 35C as illustrated in Figure 3-1. The truck was the lead vehicle, always in the lane closest to the camera. The truck, 7.3 m (24 ft.) long by 4.1 m (13.5 ft.) tall, was always followed by a car at the same intervehicle spacing as used with the car-car arrangement. In the adjacent lane, a two car pair traveled at the same speed and intervehicle spacing, with the front car's front bumper beside the truck's rear bumper.

Daylight tests measured occlusion in lanes 1 and 2, then in lanes 5 and 6. The camera was 12.2 m (40 ft.) high and the vehicles operated at 28 km/h (45 mph) for lanes 1 and 2. The camera was 15.2 m (50 ft.) high and the vehicles operated at 32 km/h (20 mi/h) for lanes 5 and 6. The headlights remained off for these two tests. Truck occlusion was then tested for both wet and dry pavements at night. The dry test was in lanes 1 and 2 at 28 km/h (45 mph). The camera height was 12.2 m (40 ft.) The wet pavement test was in lanes 5 and 6 at 32 km/h (20 mph) with the camera mounted 15.1 m (49.5 ft.) high.

This data collection consisted of performing the series of test combinations at the field test site by driving the vehicle pairs through the detection area. The video detection system recorded the passage of vehicles on videotape at the field site. For data analysis, research staff brought the recorded videotapes into the office for evaluation. This second part consisted of placing detectors in the proper location using the Autoscope™ software. Then, researchers replayed the videotaped test runs with the detectors in place, allowing the Autoscope computer software to collect and store each detector's vehicle count or vehicle speed.

3.4.3 Detector Placement

Detectors were placed at 6.1 m (20 ft.) intervals between 61 m (200 ft.) and 121.9 m (400 ft.) from the camera. Detectors were placed at 3.1 m (10 ft.) intervals between 12.2 m (40 ft.) and 61 m (200 ft.) from the camera. As previously noted, Figure 3-1 illustrates the detector interval location as part of the project study area layout.

3.5 DATA ANALYSIS

One objective of the data analysis was to determine the location where the video image processing system was able to distinguish individual vehicle identification (obtain an accurate count). Another objective was to determine the speed accuracy of the Autoscope™ system as compared to radar speeds. The level of significance chosen for this study was 0.05. The level of significance is the probability of rejecting the null hypotheses when it is in fact true. This 0.05 p-value translates to a 95 percent confidence in the decision.

3.5.1 Detection Distance Analysis

The Autoscope™ data output was analyzed and the detector location was identified when two passenger cars were counted. This detector location was plotted and an area of detection was obtained for the given camera height. This area of detection determines the video image processing system's ability to distinguish individual vehicles for traffic counting purposes.

3.5.2 Passenger Car Speed Analysis

A separate "speed-trap" detector file was created to collect the vehicle speeds of each test run. The speed obtained from Autoscope™ was the average speed of the two passenger cars. The speed obtained from Autoscope™ was compared with the speed obtained by a radar speed gun.

The video image processing system's inherent bias was recognized and the appropriate speed adjustment factors were applied to the Autoscope™ speed data. The adjusted Autoscope™ speed was compared with the speed obtained by the radar speed gun.

3.5.3 Passenger Car Interference from Adjacent Travel Lanes

Travel lane 6 data from Travel Lane Group 2 - 6 was compared with travel lane 6 data from Travel Lane Group 5 - 6 to determine if passenger cars in the adjacent travel lane (travel lane 5) affect the system's ability to distinguish individual passenger cars. The detector location was identified when two passenger cars were counted.

4.0 RESULTS

This chapter presents the results of testing described in Chapter 3.0, Methodology. The study tested passenger car detection distances at three camera heights and compared them for each of the three passenger car speeds. The study then used an analysis that determined any significant difference between the three camera heights. In the speed comparisons, project staff compared speeds generated by the Autoscope™ system with speeds obtained by a radar speed gun. The analysis compared speeds by travel lane and camera height, as well as over all travel lanes. The statistic used to determine any significant difference between radar speed data and Autoscope™ speed data was the paired t-test. Passenger car occlusion was also analyzed in this study. To study the effects of horizontal occlusion, Lane 6 data values obtained from Lane Group 2-6 were compared with Lane 6 values obtained from Lane Group 5-6.

4.1 DATA COMPILATION

Tables 4-1 through 4-3 show testing periods and dates summarized by camera height for the seven midday test days between August 10, 1995 and August 18, 1995. All testing during these midday tests occurred between the hours of 10:00 am and 4:00 pm Central Daylight Time.

TABLE 4-1. 9.1 Meter (30 Foot) Camera Height Data Collection Period

Vehicle Speed km/h (mph)	Lane Group	Test Date	Test Time Period
32 (20)	1-4	8/10/95	10:02 am - 10:44 am
32 (20)	2-6	8/10/95	10:57 am - 11:37 am
32 (20)	5-6	8/10/95	11:49 am - 12:27 pm
72 (45)	1-4	8/10/95	1:50 pm - 3:01 pm
72 (45)	2-6	8/10/95	3:14 pm - 4:04 pm
72 (45)	5-6	8/11/95	10:09 am - 11:04 am
88 (55)	1-4	8/11/95	11:18 am - 12:10 pm
88 (55)	2-6	8/11/95	1:48 pm - 2:34 pm
88 (55)	5-6	8/11/95	2:48 pm - 3:37 pm

TABLE 4-2. 12.2 Meter (40 Foot) Camera Height Data Collection Period

Vehicle Speed km/h (mph)	Lane Group	Test Date	Test Time Period
32 (20)	1-4	8/14/95	10:09 am - 10:38 am
32 (20)	2-6	8/14/95	10:43 am - 11:05 am
32 (20)	5-6	8/15/95	10:24 am - 11:02 am
72 (45)	1-4	8/15/95	11:31 am - 12:21 pm
72 (45)	2-6	8/15/95	2:08 pm - 2:53 pm
72 (45)	5-6	8/15/95	2:59 pm - 3:48 pm
88 (55)	1-4	8/16/95	10:14 am - 11:00 am
88 (55)	2-6	8/16/95	11:09 am - 11:51 am
88 (55)	5-6	8/16/95	1:13 pm - 2:02 pm

TABLE 4-3. 15.1 Meter (49 Foot - 6 Inch) Camera Height Data Collection Period

Vehicle Speed km/h (mph)	Lane Group	Test Date	Test Time Period
32 (20)	1-4	8/16/95	2:54 pm - 3:30 pm
32 (20)	2-6	8/17/95	10:12 am - 10:42 am
32 (20)	5-6	8/17/95	10:49 am - 11:19 am
72 (45)	1-4	8/17/95	12:35 pm - 1:15 pm
72 (45)	2-6	8/17/95	1:25 pm - 2:09 pm
72 (45)	5-6	8/17/95	2:18 pm - 2:56 pm
88 (55)	1-4	8/18/95	10:23 am - 11:02 am
88 (55)	2-6	8/18/95	11:10 am - 11:48 am
88 (55)	5-6	8/18/95	12:18 pm - 1:01 pm

Limitations of the number of detectors in a single computer file constricted each detector file to two lanes. Each camera height, therefore, required three computer detector files. Determining vehicle speeds required separate computer detector files — a total of 12 in all. After completion of detector files, researchers replayed the videotaped test runs in the office for analysis by the Autoscope™. For the detection distance analysis, the first detector that consistently detected two vehicles determined the detection distance for that camera height. Appendix B contains this processed data.

The nominal camera height of 15.2 m (50 ft.) as mentioned in the Methodology chapter was unachievable due to the design of the tower system. The pulley system used to hoist the camera mounting apparatus could only raise the camera to a height of 15.1 m (49 ft. - 6 in.) It is assumed that the 0.1 m (6 in.) difference is practically insignificant in these analyses.

4.2 VIDEOTAPE DISCREPANCIES

Some problems occurred while videotaping test runs in the field — the video image would unpredictably shift from side to side for no apparent reason. It was worse during the replay of recorded video than during field monitoring. This sudden movement activated the Autoscope™ count detectors, resulting in false detections. Study staff tested the Autoscope™ and supporting equipment to determine the cause of the problem. The best explanation seemed to be fluctuations in the frequency of the gasoline generator power supply. After several equipment setups were tested and numerous telephone conversations with Image Sensing Systems' technical support personnel, the source of the problem was identified. The camera used for this testing utilized the frequency of the power supply for synchronization. An unstable frequency from the gasoline generator caused the shift in the image. Technical support personnel recommended modifying the camera and disabling a crystal in the camera. Unfortunately, field test runs were complete before the solution was discovered, but the SONY 9850 VCR used in the study provided temporary relief of the synchronization discrepancies due to the type of filters it used.

4.3 DETECTION DISTANCE ANALYSIS

An Analysis of Variance (ANOVA) test was performed to determine if any statistical difference could be found in vehicle detection location between the three camera heights, travel lane location, or the interaction between camera height and travel lane location for a given vehicle speed.

The model for this analysis is:

$$X_{ijk}=\mu+A_i+B_j+AB_{ij}+\epsilon_{ijk} \qquad \text{Equation 4-1}$$

where:

X_{ijk} = k^{th} observed value when factor A is held at level I and factor B is held at level j

μ = mean detection distance

A_i = factor A effect - the effect of camera height on detection distance

B_j = factor B effect - the effect of travel lane location on detection distance

AB_{ij} = the interaction of factor A effect and factor B effect; the effect of camera height in combination with travel lane location on detection location

ϵ_{ijk} = randomness effect factor

The effects camera height and travel lane location have on detection distance are tested based on the following null and alternative hypotheses.

Null Hypotheses:

H_{o1}: The effects of camera height do not have an affect on detection distance.
H_{o2}: The effects of travel lane location do not have an affect on detection distance.
H_{o3}: The effects of camera height and travel lane location do not have an affect on detection distance.

Alternative Hypotheses:

H_{a1}: The effects of camera height do have an affect on detection distance.
H_{a2}: The effects of travel lane location do have an affect on detection distance.
H_{a3}: The effects of camera height and travel lane location do have an affect on detection distance.

The ANOVA did not compare each individual camera height with another individual camera height to determine if an individual camera height was statistically different with another individual camera height. The Bonferroni multiple comparison procedure was used to determine the statistical difference between the camera heights across all travel lanes. A Bonferroni multiple comparison analysis was also performed to determine if each individual camera height-travel lane detection data were statistically different from all other camera height-travel lane detection data.

4.3.1 32 km/h (20 mph) Passenger Car Speed Analysis

The ANOVA determined if interaction between camera height (factor A effects) and travel lane location (factor B effects) affected detection distance. From the analysis, the probability of F being less than F critical was 0.0001. The probability associated with the F-value, 0.0001, corresponds to a 99.99 percent confidence in rejecting the null hypotheses. Therefore, the null hypotheses was rejected. The analysis revealed that camera height, in combination with travel lane number, significantly affected the detection range of the system.

The detection location data for the 12.2 m (40 ft.) camera height in lane 6 was considered biased because they were collected just prior to a thunderstorm when the wind and cloud cover suddenly and unexpectedly increased. This weather condition was outside the original parameter set for this experiment. Analysis was performed without travel lane 6 detection data. The results of the analysis were the same regardless of whether lane 6 was included in the analysis. Because the interaction of camera height and travel lane location affected detection distance, further analysis isolating the individual factors was not required.

The Bonferroni multiple comparison procedure indicated a statistical difference between the 9.1 m (30 ft.) camera height, the 12.2 m (40 ft.) camera height, and the 15.1 m (49 ft. - 6 in.) camera height across all travel lanes. The Bonferroni multiple comparison procedure also indicated statistical differences between some of the individual camera height-travel lane detection data as summarized in Table 4-4. Camera height-travel lane data with the same statistical group letter designation are not significantly different. Figure A-1 in Appendix A graphically depicts the Bonferroni analysis results. Table 4-5 shows the video image system's detection range based on the minimum detection distance value of the individual camera height-travel lane data sets. Figure A-2 shows this information graphically.

4.3.2 72 km/h (45 mph) Passenger Car Speed Analysis

The detection location data for the vehicle speed of 72 km/h (45 mph) exceeded the 121.9 m (400 ft.) detection limit in four of the five travel lanes tested, regardless of the camera height. The only travel lane not exceeding the camera detection limit was travel lane 1. No analysis was performed because travel lanes 2, 4, 5, and 6 detection data exceeded the camera detection limit. No conclusions can be made from this data regarding any statistical difference between camera height and travel lane location. Figure A-3 in Appendix A graphically depicts the video image system's detection range based on the minimum detection distance value of the individual camera height-travel lane data sets.

4.3.3 88 km/h (55 mph) Passenger Car Speed Analysis

The detection location data for the speed of 88km/h (55 mph) exceeded the 121.9 m (400 ft.) detection limit in all travel lanes, regardless of the camera height. No analysis was performed because all travel lane detection data exceeded the camera detection limit. Figure A-4 graphically depicts the video image system's detection range based on the minimum detection distance value of the individual camera height-travel lane data sets.

4.4 PASSENGER CAR SPEED COMPARISON ANALYSIS

Speed readings taken in the field using a radar speed were compared to the speeds determined by the Autoscope™ system. The "speed trap" at 91.4 m (300 ft.) upstream from the camera could not be created properly because the area required to create the speed trap was near the limit of the camera's field-of-view. Therefore, only the data obtained from the "speed traps" located 30.5 m (100 ft.) upstream from the camera were compared in this study.

TABLE 4-4. Bonferroni Analysis Results - Camera Ht.-Travel Lane Detection Data

Camera Height	Travel Lane	Statistical Group
12.2 m (40 ft.)	6	A
15.2 m (50 ft.)	6	B
9.1 m (30 ft.)	6	C
15.2 m (50 ft.)	5	D
15.2 m (50 ft.)	2	E
15.2 m (50 ft.)	4	E, F
12.2 m (40 ft.)	5	F
15.2 m (50 ft.)	1	F
12.2 m (40 ft.)	4	G
9.1 m (30 ft.)	5	G
12.2 m (40 ft.)	2	H
12.2 m (40 ft.)	1	H
9.1 m (30 ft.)	4	H
9.1 m (30 ft.)	2	H
9.1 m (30 ft.)	1	I

The paired *t*-test was used to determine the differences between the passenger car speed data obtained by the radar gun and the passenger car speed data obtained by the Autoscope™ system. These values were tested based on the following null and alternative hypotheses.

Null Hypotheses:

H_o: The means μ_1 - μ_2 = 0, where μ_1 and μ_2, represent the mean speed obtained by radar and the mean speed obtained by the Autoscope™ system, respectively.

Alternative Hypotheses:

H_a: The means μ_1 - μ_2 ≠ 0, where μ_1 and μ_2, represent the mean speed obtained by radar and the mean speed obtained by the Autoscope™ system, respectively.

TABLE 4-5. Detection Range for a 32 km/h (20 mph) Passenger Car Speed

Travel Lane Number	Camera Offset m (ft.)	Camera Height		
		9.1 m (30 ft.)	12.2 m (40 ft.)	15.1 m (49 ft. - 6 in.)
		m (ft.)	m (ft.)	m (ft.)
1	5.3 (17.5)	42.6 (139.9)	48.5 (159.6)	64.0 (210.1)
2	9.1 (30.0)	45.8 (150.1)	48.8 (160.0)	73.1 (239.9)
4	16.8 (55.0)	45.7 (150.0)	61 (200.0)	70.1 (230.0)
5	17.5 (67.5)	54.8 (179.8)	57.9 (190.0)	79.2 (260.0)
6	24.4 (80.0)	91.3 (299.6)	**	97.7 (320.5)

**Data for this camera height and travel lane were taken outside the parameters set.

The paired *t*-test was performed comparing the radar speed data and the Autoscope™ speed data in the following manner:

Case 1: travel lane number and camera height
Case 2: across all travel lanes at a given camera height

From the statistical analysis, the probability of *t* being less than or equal to *t* critical was 0.0001. The p-value, 0.0001, correlates to a 99.99 percent confidence in rejecting the null hypotheses, meaning that the speed values obtained by radar and the Autoscope™ system were statistically different. The null hypothesis was rejected in both Case 1 and Case 2 comparisons. The paired t-test result was the same for all three of the passenger car speeds analyzed. Tables 4-6 through 4-8 show the mean passenger car speeds obtained by radar and Autoscope™. Figures A-5 through A-14 graphically depict the mean passenger car speed values.

Calculation of the percent difference between the Autoscope™ mean speed value and radar mean speed value resulted in values shown in Table 4-9. For a given passenger car speed, the percent difference between Autoscope™ mean speed and radar mean speed generally decreased as the camera height increased.

The percent difference in passenger car speeds was relatively constant for a given camera height, regardless of the speed. Combining all of the travel lane speed data, the passenger car speed percent difference for a camera height of 9.1 m (30 ft.) was 22.6 percent for a 32 km/h (20 mph) speed, 23.2 percent for a 72 km/h (45 mph) speed, and 22.8 percent for a 88 km/h (55 mph) speed. Only a 0.6 percent difference between the three speed percent differences existed for a camera height of 9.1 m (30 ft.) The results revealed only a 0.8 percent difference between the three speed percent differences for a camera height of 12.2 m (40 ft.) and a 1.9 percent difference for a camera height of 15.1 m (49 ft. - 6 in.)

In addition to analyzing radar speed data with the *unadjusted* Autoscope™ speed data, the analysis compared radar speed data with *adjusted* Autoscope™ speed data. Equation 4-2 gives the factor that was used to determine the speed calculation adjustment for a given camera height.

$$CAL_{adj} = \frac{h_C}{h_C + h_{VSest}} \qquad \text{Equation 4-2}$$

where:

CAL_{adj}	=	vehicle speed calculation adjustment factor
h_C	=	camera height
h_{VSest}	=	estimated vehicle signature

The vehicle signature (point of Autoscope™ detection) is assumed to be the roof of the passenger car. This assumption produces the largest speed calculation adjustment factor and factors down the vehicle speed most significantly. Table 4-10 shows the speed calculation adjustment factors applied to vehicle speeds determined by the Autoscope™ system.

This analysis used the paired *t*-test to determine differences between radar speed data and the calculated adjusted Autoscope™ speed data. The null and alternative hypotheses described in Section 4.4 formed the basis of rejection.

TABLE 4-6. Mean Passenger Car Speeds - Radar vs. Autoscope™ - 32 km/h (20 mph)

Lane Number	9.1 m (30 ft.) Camera Height			12.2 m (40 ft.) Camera Height			15.1 m (49 ft. - 6 in.) Camera Height		
	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)
1	32.66 (20.3)[1]	38.62 (24.0)	33.45 (20.6)[1]	33.45 (20.6)[1]	37.17 (23.1)	33.45 (20.6)[1]	33.45 (20.6)	37.81 (23.5)	34.27 (21.3)
2	32.5 (20.2)	39.42 (24.5)	33.79 (21.0)	32.5 (20.2)[1]	37.65 (23.4)	33.47 (20.8)[1]	32.98 (20.5)	38.94 (24.2)	35.24 (21.9)
4	31.86 (19.8)	38.94 (24.2)	33.47 (20.8)	31.70 (19.7)[1]	36.36 (22.6)	32.18 (20.0)[1]	32.5 (20.2)	37.49 (23.3)	33.95 (21.1)
5	32.66 (20.3)	40.06 (24.9)	34.43 (21.4)	32.82 (20.4)	38.29 (23.8)	33.95 (21.1)	32.34 (20.1)	36.69 (22.8)	33.31 (20.7)
6	31.86 (19.8)	39.90 (24.8)	34.11 (21.2)	31.86 (19.8)	38.29 (23.8)	34.11 (21.2)	32.98 (20.5)	36.20 (22.5)	32.82 (20.4)
Comb.	32.34 (20.1)	39.58 (24.6)	33.95 (21.1)	32.5 (20.2)	37.97 (23.6)	33.79 (21.0)	32.66 (20.3)	37.01 (23.0)	33.63 (20.9)

[1]Accepted the null hypotheses for the paired t-test comparison of the Radar passenger car speed data and the Adjusted Autoscope™ passenger car speed data

TABLE 4-7. Mean Passenger Car Speeds - Radar vs. Autoscope™ - 72 km/h (45 mph)

Lane Number	9.1 m (30 ft.) Camera Height			12.2 m (40 ft.) Camera Height			15.1 m (49 ft. - 6 in.) Camera Height		
	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)
1	70.80 (44.0)[1]	81.90 (50.9)	70.15 (43.6)[1]	71.28 (44.3)	84.15 (52.3)	74.82 (46.5)	71.76 (44.6)	83.99 (52.2)	76.27 (47.4)
2	71.28 (44.3)	87.53 (54.4)	74.98 (46.6)	71.44 (44.4)	82.70 (51.4)	73.53 (45.7)	72.41 (45.0)	85.76 (53.3)	77.88 (48.4)
4	71.44 (44.4)	92.84 (57.7)	79.48 (49.4)	70.96 (44.1)	81.90 (50.9)	72.89 (45.3)	72.73 (45.2)	82.06 (51.0)	74.66 (46.4)
5	72.24 (44.9)	87.05 (54.1)	74.98 (46.6)	71.76 (44.6)[1]	81.42 (50.6)	72.41 (45.0)[1]	72.24 (44.9)	85.92 (53.4)	78.04 (48.5)
6	71.28 (44.3)	92.04 (57.2)	78.84 (49.0)	71.92 (44.7)	86.24 (53.6)	76.75 (47.7)	72.08 (44.8)	76.75 (47.7)	71.28 (43.3)
Comb.	71.44 (44.4)	88.01 (54.7)	75.46 (46.9)	71.60 (44.5)	83.67 (52.0)	74.34 (46.2)	72.24 (44.9)	83.18 (51.7)	75.46 (46.9)

[1]Accepted the null hypotheses for the paired t-test comparison of the Radar passenger car speed data and the Adjusted Autoscope™ passenger car speed data

TABLE 4-8. Mean Passenger Car Speeds - Radar vs. Autoscope™ - 88km/h (55 mph)

Lane Number	9.1 m (30 ft.) Camera Height			12.2 m (40 ft.) Camera Height			15.1 m (49 ft. - 6 in.) Camera Height		
	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)	Radar Gun km/h (mph)	Ascope km/h (mph)	Adjusted Ascope km/h (mph)
1	87.53 (54.4)	98.63 (61.3)	84.63 (52.6)	87.85 (54.6)	104.42 (64.9)	92.84 (57.7)	88.01 (54.7)	100.40 (62.4)	91.07 (56.6)
2	88.01 (54.7)	109.09 (67.8)	93.48 (58.1)	87.53 (54.4)	103.14 (64.1)	91.71 (57.0)	88.17 (54.8)	104.10 (64.7)	94.45 (58.7)
4	88.17 (54.8)	108.12 (67.2)	92.68 (57.6)	88.01 (54.7)[1]	99.11 (61.6)	88.01 (54.7)[1]	87.85 (54.6)	100.08 (62.2)	90.91 (56.5)
5	84.47 (52.5)	108.29 (67.3)	92.68 (57.6)	87.05 (54.1)	100.72 (62.6)	89.62 (55.7)	87.85 (54.6)	102.01 (63.4)	92.52 (57.5)
6	87.53 (54.4)	113.76 (70.7)	97.50 (60.6)	87.69 (54.5)	101.53 (63.1)	90.1 (56.0)	88.17 (54.8)	98.31 (61.1)	89.30 (55.5)
Comb.	87.53 (54.4)	107.48 (66.8)	92.20 (57.3)	87.53 (54.4)	101.69 (63.2)	90.46 (56.2)	88.01 (54.7)	100.40 (62.4)	91.23 (56.7)

[1]Accepted the null hypotheses for the paired t-test comparison of the Radar passenger car speed data and the Adjusted Autoscope™ passenger car speed data

TABLE 4-9. Percent Difference Between the Mean Radar Gun Speed and the Unadjusted Mean Autoscope™ Speed

Lane Number	32 km/h (20 mph) Speed			72 km/h (45 mph) Speed			88 km/h (55 mph) Speed		
	Camera Height			Camera Height			Camera Height		
	9.1 m (30 ft.)	12.2 m (40 ft.)	15.1 m (49 ft.-6 in.)	9.1 m (30 ft.)	12.2 m (40 ft.)	15.1 m (49 ft.-6 in.)	9.1 m. (30 ft.)	12.2 m. (40 ft.)	15.1 m (49 ft.-6 in.)
1	18.5	12.6	14.1	15.7	18.2	17.0	12.7	18.9	13.9
2	21.2	15.9	17.8	22.7	15.8	18.4	24.1	17.8	17.9
4	22.3	14.3	15.3	29.8	15.5	13.0	22.7	12.6	14.0
5	22.9	16.4	13.6	20.6	13.3	18.9	28.1	15.8	16.1
6	25.0	20.5	9.6	29.0	20.1	6.6	29.9	15.8	11.4
Comb.	22.6	16.6	13.2	23.2	16.9	15.1	22.8	16.1	14.2

TABLE 4-10. Vehicle Speed Calculation Adjustment Factor

Camera Height	Adjustment Factor
9.1 m (30 ft.)	0.857
12.2 m (40 ft.)	0.889
15.1 m (49 ft. - 6 in.)	0.908

4.4.1 32 km/h (20 mph) Passenger Car Speed Comparison Analysis

For Case 1, the null hypotheses could not be rejected in only four of fifteen travel lane comparisons. These were:

- 9.1 m (30 ft.) Camera Height - Travel Lane 1
- 12.2 m (40 ft.) Camera Height - Travel Lanes 1, 2 and 4

The range of speed differences between the adjusted Autoscope™ mean speed values and radar mean speed values was from 0.0 to 2.3 km/h (0.0 mph to 1.4 mph). The statistical comparison between radar speed data and the adjusted Autoscope™ speed data combining the speed data of all travel lanes for a given camera height also rejected the null hypotheses (p-value = 0.0001). Table 4-6 shows the adjusted Autoscope™ mean passenger car speeds and radar mean passenger car speeds. Figures A-5 through Figure A-7 graphically depict the mean passenger car speed values.

4.4.2 72 km/h (45 mph) Passenger Car Speed Comparison Analysis

For Case 1, the null hypotheses could not be rejected in only two of fifteen travel lane comparisons. These were:

- 9.1 m (30 ft.) Camera Height - Travel Lane 1
- 12.2 m (40 ft.) Camera Height - Travel Lane 5

The range of speed differences between the adjusted Autoscope™ mean speed values and radar mean speed values was from 0.6 to 8.1 km/h (0.4 to 5.0 mph). The statistical comparison between radar speed data and the adjusted Autoscope™ speed data combining the speed data of all travel lanes for the given camera height rejected the null hypotheses (p-value = 0.0001). Table 4-7 shows the adjusted Autoscope™ mean passenger car speeds and radar mean passenger car speeds. Figure A-8 through Figure A-10 in Appendix A graphically depict the mean passenger car speed values.

4.4.3 88km/h (55 mph) Passenger Car Speed Comparison Analysis

For Case 1, the null hypothesis could not be rejected in only one of fifteen travel lane comparisons. This was:

- 12.2 m (40 ft.) Camera Height - Travel Lane 4

The range of speed differences between the adjusted Autoscope™ mean speed values and radar mean speed values was from 0.0 to 10 km/h (0.0 mph to 6.2 mph). The statistical comparison between radar speed data and the adjusted Autoscope™ speed data combining the speed data of all travel lanes for the given camera height rejected the null hypotheses (p-value = 0.0001, 0.0017). Table 4-8 shows the adjusted Autoscope™ mean passenger car speeds and radar mean passenger car speeds. Figure A-12 through Figure A-14 graphically depict the mean passenger car speed values.

4.4.4 Percent Difference Passenger Car Speed Analysis - Adjusted Autoscope™ Speeds

Table 4-11 shows the percent difference in the mean passenger car speeds. Analyzing the individual travel lane percent difference values revealed no trends or patterns in the data; however, combining the travel lane speed data indicated a trend. The 9.1 m (30 ft.) camera height data revealed a 5.1 percent difference in the passenger car speed for a 32 km/h (20 mph) passenger car speed, a 5.6 percent difference for a 72 km/h (45 mph) passenger car speed and a 5.2 percent difference for a 88 km/h (55 mph) passenger car speed. The data also showed a 0.7 percent difference between the three speed percent differences for the 12.2 m (40 ft.) a camera height and a 1.7 percent difference between the three speed percent differences for the 15.1 m (49 ft. - 6 in.) camera height.

The largest decrease in percent difference occurred between the 9.1 m (30 ft.) camera height and the 12.2 m (40 ft.) camera height -- between 1.5 percent and 2.0 percent when combining travel lane speed data. The percent difference between the 12.2 m (40 ft.) camera height and the 15.1 m (49 ft. - 6 in.) camera height was between 0.5 percent and 0.7 percent.

4.5 DETECTION LOCATION INFLUENCES FROM PASSENGER CARS IN ADJACENT LANES

The paired *t*-test was used to determine the statistical difference between travel lane 6 detection location data from lane group 2-6 and travel lane 6 detection location data from lane group 5-6 for a given camera height and vehicle speed. The travel lane 6 detection location data were tested based on the following null and alternative hypotheses.

TABLE 4-11. Percent Difference Between the Mean Radar Gun Speed and the Adjusted Mean Autoscope™ Speed

Lane Number	32 km/h (20 mph) Speed			72 km/h (45 mph) Speed			88 km/h (55 mph) Speed		
	Camera Height			Camera Height			Camera Height		
	9.1 m (30 ft.)	12.2 m (40 ft.)	15.1 m (49 ft.-6 in.)	9.1 m (30 ft.)	12.2 m (40 ft.)	15.1 m (49 ft.-6 in.)	9.1 m (30 ft.)	12.2 m (40 ft.)	15.1 m (49 ft.-6 in.)
1	1.6	0.1	3.6	-0.8	5.0	6.3	-3.4	5.7	3.5
2	3.9	3.1	7.0	5.1	2.9	7.5	6.3	4.7	7.1
4	4.8	1.6	4.7	11.3	2.7	2.6	5.2	0.1	3.5
5	5.3	3.5	3.1	3.9	0.7	8.0	9.8	2.9	5.4
6	7.1	7.1	-0.5	10.5	6.7	-3.2	11.3	2.9	1.2
Comb.	5.1	3.6	2.9	5.6	3.9	4.6	5.2	3.2	3.7

Null Hypothesis:

H_o: The means μ_1 - μ_2 = 0, where μ_1 and μ_2, represents travel lane 6 detection data from lane group 2-6 and travel lane 6 detection data from lane group 5-6, respectively.

Alternative Hypothesis:

H_a: The means μ_1 - μ_2 ≠ 0, where μ_1 and μ_2, represents travel lane 6 detection data from lane group 2-6 and travel lane 6 detection data from lane group 5-6, respectively.

4.5.1 32 km/h (20 mph) Passenger Car Speed Analysis

From the analysis of the travel lane 6 detection distance data for the 9.1 m (30 ft.) camera height, the probability of T being less than or equal to t critical was 0.0037. Therefore, the null hypotheses was rejected and the travel lane 6 detection distance data obtained from travel lane group 2-6 was statistically different than the travel lane 6 detection distance data from travel lane group 5-6.

The analysis of travel lane 6 detection distance data for the 12.2 m (40 ft.) camera height also rejected the null hypotheses. The probability of T being less than or equal to t critical was 0.0039. From the analysis of travel lane 6 detection distance data for the 15.1 m (49 ft. - 6 in.) camera height, the probability of T being less than or equal to t critical was 0.6408. Therefore, the null hypotheses was accepted and the travel lane 6 detection distance data obtained from travel lane group 2-6 was not statistically different than the travel lane 6 detection distance data obtained from travel lane group 5-6. Figure A-15 found in Appendix A graphically depicts the relationship between the minimum and mean detection distance with and without the influence of the travel lane 5 passenger car pair.

4.5.2 72 km/h (45 mph) Passenger Car Speed Analysis

The travel lane 6 detection distance data analysis rejected the null hypothesis, regardless of the camera height. However, the reason for the null hypothesis rejection was due to the lack of variability of the data. In every test run, the first detector in the travel lane accurately detected the number of passenger cars in that lane as shown in Appendix B. Figure A-16 in Appendix A graphically shows the relationship between the minimum and mean detection distance with and without the influence of the travel lane 5 passenger car pair.

4.5.3 88 km/h (55 mph) Passenger Car Speed Analysis

The travel lane 6 detection distance data analysis rejected the null hypotheses for the 9.1 m (30 ft.) camera height due to a lack of data variability. From the analysis of the travel lane 6 detection distance data for the 12.2 m 40 ft. camera height, the probability of t being less than or equal to t critical was 0.0295. Therefore, the travel lane 6 detection distance data obtained from travel lane group 2-6 was statistically different than the travel lane group 5-6 and the null hypotheses was rejected.

From the analysis of travel lane 6 detection distance data for the 15.1 m (49 ft. - 6 in.) camera height, the probability of *t* being less than or equal to *t* critical was 0.4134. Therefore, the travel lane 6 detection distance data obtained from travel lane group 2-6 was not statistically different than the travel lane 6 detection distance data obtained from travel lane group 5-6 and the null hypotheses was accepted. Figure A-17 in Appendix A graphically shows the relationship between the minimum and mean detection distance with and without the influence of the travel lane 5 passenger car pair.

4.6 NON-MIDDAY TESTS

Testing during non-midday time periods was more limited than tests discussed above that were run during the midday. There were fewer lanes used for each speed and camera height, but there were at least 10 runs for each set of selected conditions. During early dusk and late dawn periods, testing occurred without headlights. However, testing in earlier morning and later evening required headlights. Wet pavement testing only occurred in lanes 5 and 6 under full darkness, with water provided by a water truck at the site. All other testing used dry pavement.

4.6.1 Passenger Cars Day versus Night

Autoscope™ detection during daylight conditions compared to night reveals little or no difference in detection distance. Comparing a small sample of night tests to 12 daylight runs using the same camera height of 12.2 m (40 ft.) and vehicle speed of 32 km/h (20 mi/h) indicates detection distances that are similar. Night tests with occlusion indicated a detection distance of 115.9 m (380 ft.) in lane 6. Daylight tests with occlusion indicated detection at very similar distances from 109.8 to 122.0 m (360 ft. to 400 ft.) in lane 6. The detection ranges for both day and night are graphically depicted in Figure A-17.

Table 4-12 shows the results of night speed comparisons between radar and Autoscope™, some occluded and some non-occluded. The camera height was 12.2 m (40 ft.) and speeds were nominally 32.2 km/h (20 mph). Adjusted Autoscope™ mean speeds were always higher than radar mean speeds, with only one exception. The differences are generally larger than those from midday tests, implying that the Autoscope™'s speed accuracy is less in poor lighting conditions than it is under optimum lighting conditions. The *t* test indicated that Autoscope™ speeds were significantly different from radar speeds. Figure A-18 is a graphic representation of this speed data.

4.6.2 Passenger Car Sunrise Tests

This series tested car combinations at sunrise with headlights on and off at 32 km/h (20 mph) using a camera height of 9.1 m (30 ft.) and offset of 9.1 m (30 ft.) from lane 1. The detection distance for lane 1 was 39.6 m (130 ft.) with headlights off and 48.8 m (160 ft.) with the headlights on. In lane 3, the system properly detected vehicles at 54.9 m (180 ft.) with the headlights off and 57.9 m (190 ft.) with the headlights on. Detections occurred in the occlusion tests in lanes 4 and 5 at 67.1 m (220 ft.) with the headlights off and 61.0 m (200 ft.) with the headlights on. Figure A-19 presents these detection distances graphically.

The camera height was 9.1 m (30 ft.), and the vehicles operated at 32.2 km/h (20 mph) at the test site where the sunrise investigation was measured. The camera offsets from vehicles in this investigation were similar to the midday tests. Tables 4-13 and 4-14 summarize the results; Figures A-20 and A-21 show them graphically. It should be noted that the lanes being monitored are different between Table 4-13 and Table 4-14. Comparing results, it would appear that Autoscope™ speeds are closer to radar speeds in Table 4-13, although the variation is probably randomly based on other tabulated results. Results of the *t* test indicated significant differences between Autoscope™ and radar speeds.

4.6.3 Day and Night Truck Occlusion

In daylight tests, the truck occluded other vehicles, especially those behind the truck when it passed in the lane closest to the camera. Daylight tests indicated occlusion to be a problem for all runs in lanes 1 and 2. Only one detection resulted from the entire test range for these two lanes. In lane 5, however, at 28 km/h (45 mph), the Autoscope™ system's vehicle count was accurate at a distance of up to 122.0 m (400 ft.) from the camera. In lane 6, this distance was 116.0 m (380 ft.) Although the detection count was accurate, it was not clear if the truck was detected in place of the car in lane 6 (the top of the truck might have been detected by the lane 6 detector).

Night tests resulted in inaccurate vehicle counts, not only for vehicles beside the truck but also for vehicles traveling at 1.5 second headways directly behind the truck. The Autoscope™ only detected one vehicle per lane during all of the truck night runs. There should have always been two. Single detections occurred from beginning to end as the vehicles passed through the detection zone. Night testing consisted of dry pavement tests in lanes 1 and 2 and wet pavement tests in lanes 5 and 6. Other conditions included camera height of 12.2 m (40 ft.) and nominal speed of 28 km/h (45 mph) in lanes 1 and 2 and nominal speed of 32 km/h (20 mph) with the camera mounted 15.2 m (50 ft.) high in lanes 5 and 6. Tables 4-15 and 4-16 tabulate speed comparisons for these conditions. Figures A-22 and A-23 provide graphic depictions of this speed data. Results of *t* tests indicated that Autoscope™ and radar speeds were significantly different for the truck runs.

4.6.4 Inclement Weather

The weather has not been suitable for these tests during a time period when both vehicles and personnel were available to conduct the tests. This requires a relatively high intensity of rainfall or fog for a sufficiently long time period.

Table 4-12. Mean Passenger Car Speeds - Radar Gun vs. Autoscope™ - 32.2 kph (20 mph) at 12.2 m (40 ft.) Camera Height

Lane Number	12.2 m (40 ft.) Camera Height - No Occlusion[1]				12.2 m (40 ft.) Camera Height - No Occlusion				12.2 m (40 ft.) Camera Height - Occlusion			
	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference
1	32.0	39.4	35.1	9.5	32.5	49.9	44.4	36.6				
2					31.2	37.3	33.1	6.2				
3												
4	32.3	40.0	35.2	9.5	32.0	40.4	35.9	12.1				
5									32.0	32.2	28.6	10.6
6					31.4	38.3	34.1	8.7	32.0	38.3	34.1	6.5
Comb.	32.2	39.7	35.2	9.5	31.8	41.5	36.9	15.9	32.0	35.3	31.4	8.6

[1] Headlights Off

Table 4-13. Mean Passenger Car Speeds - Radar Gun vs. Autoscope™ - 32 km/h (20 mph) At 9.1 m (30 ft.) Camera Height - Non-Occlusion Testing

Lane Number	9.1 m (30ft.) Camera Height - Headlights On				9.1 m (30 ft.) Camera Height - Headlights Off			
	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference
1	32.2	39.3	33.6	4.5	32.0	36.8	31.5	1.5
2								
3	32.3	42.3	36.2	11.9	32.2	40.1	34.3	6.5
4								
5								
6								
Comb.	32.3	40.8	34.9	8.2	32.1	38.5	32.9	4.0

Table 4-14. Mean Passenger Car Speeds - Radar Gun vs. Autoscope™ - 32.2 km/h (20 mph) At 9.1 m Camera Height - Occlusion Testing

Lane Number	9.1 m (12.2 ft.) Camera Height - Headlights On				9.1 m (12.2 ft.) Camera Height - Headlights Off			
	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference
1								
2								
3								
4	31.9	40.5	34.8	9.1	32.3	42.5	36.4	12.4
5	31.9	42.8	36.7	15.2	31.9	32.7	28.0	12.1
6								
Comb.	31.9	41.7	35.8	12.2	32.1	37.6	32.2	12.3

Table 4-15. Mean Passenger Car/Truck Speeds - Radar Gun vs. Autoscope™ - 72.4 km/h (45 mph) At 12.2 m (40 ft.) Camera Height - Occlusion Testing

Lane Number	12.2 m (40 ft.) Camera Height - Headlights On				12.2 m (40 ft.) Camera Height - Headlights Off			
	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference
1	72.1	103.5	85.0	17.9				
2	71.6	105.1	86.2	20.4				
3								
4								
5					72.9	106.5	87.5	20.1
6					73.0	124.4	102.2	40.0
Comb.	71.9	104.3	85.6	19.2	73.0	115.5	94.9	30.1

Table 4-16. Mean Passenger Car/Truck Speeds - Radar Gun vs. Autoscope™ - 32 km/h (20 mph) 15.1 m (49 ft. - 6 in.) Camera Height - Occlusion Testing

Lane Number	15.1 m (49 ft. - 6 in.) Camera Height - Headlights On				15.1 m (49 ft. - 6 in.) Camera Height - Headlights Off			
	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference	Radar Gun (km/h)	Ascope (km/h)	Adjusted Ascope (km/h)	Adjusted % Difference
1					32.3	37.5	31.9	1.5
2					32.5	37.0	31.5	3.0
3								
4								
5	31.9	32.8	27.8	12.6				
6	32.0	38.5	32.7	2.0				
Comb.	32.0	35.7	30.3	7.3	32.4	37.3	31.7	2.3

5.0 COST CONSIDERATIONS

5.1 INTRODUCTION

Accurate, dependable, and cost-effective methods of monitoring traffic are essential to developing and maintaining an effective and efficient transportation network. Without accurate and timely data, it is impossible to manage the system efficiently. Data storage requirements mandate data collection and storage systems that are accurate over time; data monitoring devices that contribute to real time system control strategies must also generate timely data. Data collection provides the information used in the decision process of control strategies, incident management procedures, motorist information displays, and a number of other activities relevant to the safety and efficiency of streets, highways, and freeways. Data collection includes measurement of traffic conditions. Once collected, data can be used in real time to make management decisions, or stored to provide a historical record of traffic conditions.

Specific reasons for collecting vehicular speed, volume, density, and other data include input for policy decisions related to mobility and protecting the transportation infrastructure and street and highway control strategies. An example of the need for policy related data is the Highway Performance Monitoring System (HPMS) *(36,37,38)*. Its purpose is to provide a database for the roadway-related data most frequently needed by the Federal Highway Administration (FHWA) for policy development and response to legislative issues of concern to Congress. The HPMS was based on the statistical principle utilizing a limited number of data items for all road and street mileage, and very detailed data for a sample of sections in each functional class of roadway.

Somewhat in contrast to the HPMS data for widespread application are the more localized data needs of a particular facility or corridor. State and local jurisdictions collect data that are facility-specific and that are used for monitoring and control on that same facility on a real time basis. This localized surveillance and control may use the same surveillance equipment as needed for HPMS or other historical data needs.

Site specific equipment includes all detectors that collect data at a specific location along the roadway. Examples of commonly used detectors are: inductive loop detectors (ILD), pneumatic tubes, magnetometers, tapeswitches, and piezoelectric sensors. Categories of site specific data collection equipment are embedded, on-pavement, and above pavement (or non-intrusive) detectors. The inductive loop detector continues to be the most commonly used form of detector, even though its weaknesses are widely recognized and other detectors are being marketed to replace ILDs. Undesirable features of inductive loops include the need to saw the pavement (causing weakness) and the need to close traffic lanes during installation (causing motorist delay, excess fuel usage, additional exhaust emissions, and possibly increased vehicle crashes). Exposure of public employees to moving traffic while installing inductive loops is also a major concern, especially in high speed traffic.

Some of the emerging *non-intrusive* technologies that have potential for replacing ILDs are microwave and radar, laser, ultrasonic, infrared, and video image processing systems. Recent and ongoing studies are evaluating these sensors from a performance standpoint *(39,40)*, but there seems to be little information available on comparative costs, other than initial hardware cost. Table 2-1 lists some of the current technologies and products being tested and their initial costs. It should be noted that unit costs may vary depending on quantity purchased. Of this list of detectors, the one that will be considered in this cost analysis in more detail is video image processing (VIP). These initial costs are but one consideration in determining the viability of detection technologies. Their accuracy in all weather and lighting conditions and costs to keep them functioning properly are equally important.

The sections that follow address life cycle costs of inductive loop detectors and video image processing systems, first by citing cost information found in the literature and then by evaluating cost information documented by the Texas Department of Transportation (TxDOT). The analysis of costs for the two categories of sensors divides overall costs into initial costs and maintenance costs. Initial costs of ILDs come from recent TxDOT installations in different geographic areas of the state. Literature cost sources are also considered and are used for comparison with TxDOT costs. Initial costs of video detection systems come from the literature and from recent purchases made by the Texas Transportation Institute (TTI). Maintenance costs of both ILDs and video detection systems are not as easily quantified as initial costs. This element of the cost comparison relies upon the available evidence from TxDOT and from recent experience of one agency that kept detailed records of maintenance on video systems.

An additional cost that should be considered, although difficult to quantify, is vehicle crashes resulting from lane closures. This includes the possible increase in crashes due to the lane closures as well as crashes involving employees installing traffic control devices and then working in close proximity to moving traffic to install loops. Unfortunately, determining this increase would probably require an extrapolation from a larger general workzone database that may not necessarily apply to a short-term project like loop installation.

A brief description of the components of inductive loops and video systems was provided in Chapter 2, but the brief overview provided below will be instructive in discussing the cost components described in this chapter. The inductive loop detector consists of three parts: the loop itself, the lead-in cable, and the detector unit. The *loop* consists of shielded wire typically installed in a 6.3 mm to 9.5 mm (1/4 in. to 3/8 in.) wide saw cut in the pavement typically resulting in a rectangular shape when viewed from above the pavement. The *lead-in cable* is used to connect the loop to the detector unit. It normally consist of two types of cable (wire). The portion of the lead-in cable between the loop and the pull box is simply an extension of the loop wire. The total length of the lead-in wire is the distance from the loop to the detector unit. The *detector unit* is sometimes referred to as the detector amplifier. It consists of electronics that interpret the changes in the electrical properties of the loop when a vehicle passes over the loop. This detector unit is located in a cabinet off the roadway, away from the loop.

Video detection systems consist of a *processing unit*, one or more *cameras*, system *software*, and ancillary mounting hardware and cabling. Typical mounting arrangements place the cameras on existing or new poles at heights of 7.6 to 12.2 m (25 to 40 ft.), requiring coaxial and power cables from the cameras to the processing unit located in the cabinet. Video processors considered in this paper are equipped to interface with the signal controller cabinet without modification, so the cost comparison includes only those components needed for detection and communication with the cabinet. For ILDs, it includes the loop, wiring, pull boxes, conduit, and detector amplifier. For video systems, it includes cameras, processor, cabling, and mounting hardware.

5.1.1 Literature Search

A literature search revealed limited information on costs of non-intrusive detectors, and even less on life cycle costs of ILDs or comparisons of inductive loop detector costs and non-intrusive detection costs. Shuldiner, in a report entitled, "Cost Effective Investment Strategies for Incident Management on a Section of the Massachusetts Turnpike," *(41)* cites costs of inductive loop detectors as determined by Edmands *(42)* in the range of $1,200 to $12,000. The $1,200 estimate from Tarnoff, at Farradyne Systems, Inc., is the capital cost for each loop detector. The $12,000 cost came from a report done for the TRANSCOM project, which also cited the annual maintenance and operational cost per loop of $2,500. Shuldiner concludes that the $12,000 estimate is high compared to estimates from other sources, which range from $1,200 to $3,250. This cost apparently excludes traffic control cost and motorist delay during installation; but it includes the following items: detector amplifiers; local controllers, which process the loop detector information yielding speed, volume and occupancy; communication equipment for transmission of processed data to the control center; and a cabinet for the local processor and control equipment *(43)*.

In Reference *(41)*, dated 1993, there was reference to a consultant's estimate of the costs of inductive loop components in Massachusetts. In this estimate, conduit cost for the power source and communication system was $82 per meter ($25 per ft.) installed. The pavement cuts cost approximately $49.20 per meter ($15 per ft.), with a total length of cut per detector of 79 m (24 ft.) One loop amplifier was required per loop at a cost of $400 each. The cabinet which houses the amplifier and processing equipment for each detector costs between $750 and $1,000 installed.

Michalopoulos and Anderson *(44)* determined that the additional initial investment in wide area detection (video based) over ILDs yielded returns on a Minnesota freeway ranging from a low of 1.25-to-1 to a high of 18.4-to-1. Even though not all of their cost assumptions were clear, the following details were available. The comparison scenario was a freeway setup where NEMA 170 controllers were already available for ramp metering control, so the controller costs were excluded in loop costs except for one location out of seven. Other costs were: actual loop cost of $560 each, two conductor #14 lead-in wire cost of $2.07 per meter ($0.63 per ft.), and four-channel inductive loop detector amplifiers at $153 each.

This source also provided costs of wide area detection components. Components included fixed focal length cameras, camera enclosures, mounting hardware, video processors, and cabling for video and power transmission. Their reported average processor system cost was $7,000 per camera in 1993, although this cost would obviously vary with the number of cameras used per processor. Their cost for RG-11 coax cable was $2.46 per meter ($0.75 per ft.), and the three conductor #10 power cable cost $3.28 per meter ($1.00 per ft.) All prices for loop and video detection components include materials and labor to install.

Michaloupolos and Anderson also estimated traffic control costs for both loops and video detection installations. They assumed the "typical" Minnesota DOT three percent of project cost for traffic control. This three percent of the total system cost, divided by the total number of loops was $40 per loop. Even though no lane closures were required for video, they assumed an arbitrary value of $20 per camera for their estimate of traffic control costs for video installation.

Finally, the study acknowledged motorist delay costs for loop installation. They used the KRONOS freeway simulation software to estimate delay to motorists based on an assumed value of lost time of $10.65 per hour. Traffic delay calculations assumed typical roadway volumes based on historical loop counts between 9:00 am and 2:30 pm, a two-hour duration for each loop, and a minimum length of lane closure of 370 m (1,200 ft.) It should be noted that the simulation program constraints only allowed closure limits in the range of 60 m to 245 m (200 ft to 800 ft.) They point out that the program therefore underestimates actual delay. Furthermore, they estimated two-lane roadway capacity of 4,800 vehicles per hour (based on previous traffic counts) and constricted capacity of 1,500 vehicles per hour with one lane closed, based on capacity reduction documented in other work zones. The estimated delay for the entire four-lane roadway for loop installation was estimated to be 15,400 vehicle-hours, in addition to 34,000 L (9,000 gal.) of extra fuel. The $10.65 per vehicle-hour delay included the cost of extra fuel and lost time as the indirect cost borne by the users of the roadway. The resulting user cost due to delay during loop installation was $164,000. This study accounted for loop failure and maintenance costs by the fact that pavements in Minnesota are overlaid historically on an average of once every eight years, requiring new loops. One final detail in this cost comparison was that it assumed no cost for installing new poles for video cameras.

5.2 ILD COSTS AT INTERSECTIONS

The elements of life-cycle cost of inductive loops that need to be considered include: installation costs; maintenance costs of the loop, cable, and detector unit; traffic control; motorist delay; additional pavement maintenance costs; and costs related to increased crash rates. Some of these factors vary by intersection versus freeway, pavement type, and area of the state. Installation costs of inductive loops on freeways may include longer runs from the loops to the cabinet as compared to intersections. Pavement cutting in concrete takes longer than in asphalt if depth and width of cut are the same. In the northern parts of the state, ice and snow may cause maintenance costs to be higher than areas to the south. Some TxDOT districts replace failed loops in concrete by simply "routing out" the old loop wires and putting new wires back in their place. This takes less time than cutting new loops, and is therefore less expensive. In asphalt, districts typically replace failed loops by installing completely new installations. Exogenous factors such as pavement condition and damage from other maintenance and construction activities also cause variability in the costs of maintaining loops. TTI conducted a limited survey of some TxDOT districts to determine their costs to install ILDs on freeways and at intersections (primarily on frontage roads). Further analysis considers only intersections, excluding freeway mainlanes.

TxDOT districts use a variety of loop configurations at intersections, depending on approach speeds, signal phasing, district preferences, and right-of-way constraints. Bids submitted by contractors for cutting loops are based on linear measurement of saw cut, so installation costs increase with increasing size and/or the number of loops per intersection. The most accurate method of determining the initial cost of installation is to use documented installation costs for recent installations. Fortunately, these costs were available for four intersections in Paris, Texas. Other districts providing loop cost information were: Dallas, El Paso, Ft. Worth, and Houston.

5.2.1 Dallas District

The specifications used in Dallas for loop installation are included in Appendix _. They use a gross estimate for the cost of loops of $13.12 per linear meter ($4.00 per linear ft.), which is probably high, according to district personnel. The actual cost is approximately $6.56 to $9.84 per meter ($2 to $3 per ft.) Their cost of cutting in asphalt pavement is very close to the same cost as in asphalt because they cut a wider cut in asphalt (9.5 mm versus 6.35 mm — [3/8 in. versus 1/4 in.] in concrete). They use "loop duct" in asphalt which requires a wider cut. In both cases, they cut 31.75 mm (1 1/4 in.) deep. The loop duct material is a polyethylene jacket that encases and protects the loop wire in asphalt. It is a solid tube (jacket) and not a liquid material that cures with time. The district currently uses what they call the "Blue Book," which is a 1993 publication of costs. The 1995 publication, called the "Red Book", will be their new document and it will use metric units. Loop duct is a little more expensive than plain wire.

The primary cost difference between the freeway mainlanes and frontage roads (signalized intersections) is in the cost of traffic control. For frontage roads, the Department simply uses flaggers and a few signs, so the cost for mainlane construction or maintenance is higher. They estimate $200 to $300 for each traffic control setup on mainlanes, which is derived from $1,000 to $1,500 per month. The closure of two lanes costs approximately 1.5 times the cost of a one lane closure. The spokesman stated that motorist delay is not a big cost factor.

5.2.2 Ft. Worth District

The Ft. Worth District has a contract for installing or repairing inductive loops at signalized intersections. Their cost is based on linear foot of saw cut; it is $12.79 per meter ($3.90 per lin. ft.) or if duct protected it is $16.07 per meter ($4.90 per ft.) Conduit (25mm — [1 in. PVC]) from the edge of roadway to the pull box costs $19.68 per meter ($6.00 per ft.) to install. Ground boxes (pull boxes) are already installed so repair costs exclude them. The cost of wire from the corner of the loop to the pull box is provided below, but the amount needed varies; it could vary from 0.6 to 3.6 m (2 to 12 ft.) Table 5-1 summarizes these costs.

Table 5-1. Ft. Worth Loop Component Costs

Material	Unit	Cost
Loop wire with duct	ft	$0.14
Plain loop wire	ft	$0.06
2-conductor shielded	ft	$0.15
Loop detector (1 channel)	each	$72.29

Note: 1 m = 3.28 ft.

In the Ft. Worth District, large loops have two turns of wire. For example, a 1.8 m by 9.1 m (6 ft. by 30 ft.) loop has 43.9 m (144 ft.) of wire. Therefore, the cost of a 1.8 m by 9.1 m (6 ft. by 30 ft.) loop, installed in the outside lane with a 3.0 m (10 ft.) wide shoulder with a pull box that is 3.7 m (12 ft.) off the edge of the shoulder and distance from pull box to cabinet of 15.2 m (50 ft.) would be as shown in Table 5-2.

Table 5-2. Itemized ILD Costs in Ft. Worth

COST ITEM	COST
Saw cut: 85 ft x $4.90/ft	$ 416.50
Loop wire: (144 + 50 + 12) x $0.14	28.84
Lead in from corner of loop to pull box:	
Conduit: 12 ft x $6/ft	72.00
Wire: 25 x 2 x $0.14/ft	7.00
Pull box to cabinet (2 conductor shielded): 50 x $0.15	7.50
Loop detector:	72.29
TOTAL	$ 604.13

Note: If power header is used, add additional loop wire.
1 meter = 3.28 feet

For repairs in concrete, the Ft. Worth district sometimes replaces the loop, but this depends upon whether a crack or joint caused the failure. If it appeared that a crack or joint caused the failure, the district replaces the entire loop nearby. Otherwise, they rout out the old loop and replace it with new wire. For repairs in asphalt, the Ft. Worth district replaces the entire loop every time.

The number of detector amplifiers depends upon the number of loops. They have as many as 20 detector amplifiers in one controller cabinet for one intersection. Each intersection is unique. TxDOT frequently uses duct wire on city streets because they only do maintenance to the right-of-way line. Also, installation crews may use existing 76 mm (3 in.) conduit that already exists for the signal to run loop wire to the cabinet instead of installing new conduit. They have a pay item for this just in case it is needed.

Traffic control costs were included in this cost of $12.79 or $16.07 per m ($3.90 or $4.90 per ft.) and the contractor is expected to take care of that. Motorist delay was not a significant factor during their installation activities, according to district personnel. An exception is a two lane, two way roadway, although they still install during off-peak hours reducing delay.

Their loops are installed in several different configurations depending on intersection speed and number of lanes. Typical loop sizes are 1.8 m by 9.1 m (6 ft. by 30 ft) -- normal or quadrapole, 1.8 m by 10.7 m (6 ft by 35 ft), and 1.8 m by 18.3 m (6 ft by 60 ft). Every intersection has at least one of these on each approach. The district representative commented that computing the maintenance costs of loops due to failures would take a considerable amount of time.

5.2.3 Houston District

The Houston District also supplied information related to ILD replacements at signalized intersections that could be used to calculate periodic maintenance costs. The number of failures discovered over a time period of seven years is as shown in Table 5-3. There were as few as 42 loop failures discovered in a year's time and as many as 271 loop failures discovered in the 804 signalized intersections under TxDOT jurisdiction. It should be noted that other loop malfunctions required technicians to travel to the intersections that are not reflected in the table.

There are some difficulties in trying to quantify failure rates at the Houston intersections over a time period of several years, because the district has changed its loop policy and equipment over that time period. When they first started installing detectors for signals, the district used quadrapoles in left turn bays but not on through lanes. Now, the district has discontinued the installation of quadrapoles. In approximately 1994, they began using four 1.8 m by 1.8 m (6 ft. by 6 ft.) loops in turn bays. In approximately 1993, the district began using multiple loops on relatively high speed approaches to avoid dilemma zones. They stopped installing fixed time signal equipment in approximately 1984, but these systems continued operation until approximately November 1995. They are currently changing their policy again. The current typical loop detector layout is a 1.8 m by 12.2 m (6 ft. by 40 ft.) loop at the stop bar, but sometimes access to adjoining property is a problem if a curb cut exists within the 12.2 m (40 ft.) dimension.

Because TxDOT provided the actual length of saw cut needed to replace failed loops, some of these changes will not significantly compromise the accuracy of cost calculations. However, the fact that some of the 804 intersections were not traffic actuated (had no detectors) until recently will be a source of error. The estimate of the cost per intersection will be conservative because it assumes that all of the intersections had loops, that 100 percent of loop failures were discovered, and that no maintenance costs besides replacements were incurred. Table 5-3 shows the resulting cost of loop replacements per intersection per year with a mean value of annual cost per intersection of approximately $330. Because of the conservative nature of this estimate, it is increased to $400 per intersection for further analysis. It should be noted that this calculation is within the range of costs calculated for the Paris intersections.

Table 5-3. Replacement Cost for Failed Loops at Intersections in the Houston District

Year	No. ILD Failures Discovered	Lin. Ft.	Replacement Cost + TC	Cost per Intersection [b]
1989	42	4,574	$65,100	$80.97
1990	271	23,795	$420,050	$522.45
1991	195	16,162	$302,250	$375.93
1992	211	17,561	$327,050	$406.78
1993	177	14,280	$274,350	$341.23
1994	84	4,388	$130,200	$161.94
1995	208	11,250	$322,400	$401.00
1996	157[a]	11,650	$243,350	--

[a] Through June 1996
[b] Total of 804 intersections under TxDOT jurisdiction, costs exclude delay to motorists

5.2.4 Paris District

The TxDOT District office in Paris had recently installed ILDs at two intersections that previously used fixed time control. Paris is a small city in extreme northeast Texas with a population of approximately 25,000. The two intersections on the north and east sides of Paris involve US 82, Business 82, and US 271. When TxDOT built the bypass around the north side of the city, it became the new US 82, and the old US 82 became Business 82, which passes through downtown. Both are generally east-west facilities, while US 271 generally runs north-south. The new US 82 was built as an expressway with some access control, forming grade separations and signalized intersections on each side of the roadway at US 271/US 82 and US 82/Business 82.

Figures 5-1 and 5-2 show the intersection layouts for the four intersections, to include the loop configurations. Tables 5-4 and 5-5 summarize the installation costs of these loops installed in asphalt pavement. The total number of ILDs installed at the US 82/Business 82 intersections was 14

Each configuration was 1.8 m by 9.1 m (6 ft. by 30 ft.) with 1.8 m (6 ft.) power header and 22 each 1.8 m by 1.8 m (6 ft. by 6 ft.) loops. The intersection of US 82/US 271 required 14 loops. Each configuration for these loops was 1.8 m by 15.2 m (6 ft. by 50 ft.) with 1.8 m (6 ft.) power headers and 14 each 1.8 m by 1.8 m (6 ft. by 6 ft.) advance loops. All costs were provided by district TxDOT personnel. The district provided traffic control, so they estimated the manpower costs and use of equipment costs. It should be noted that these costs would have been substantially higher if they had hired a contractor to provide the services. The total initial cost of detection using ILDs for the US 82/US 271 intersections was $38,234; for the US 82/Bus. 82 intersection, the total initial cost was $39,560.

The Paris District also estimated loop replacement costs as shown in Table 5-6. Estimation of frequency of replacement is more difficult because district personnel did not keep complete maintenance records on inductive loops. District personnel can accurately estimate the cost of loop replacement, but the frequency of replacement is more difficult. Table 5-6 shows that replacement of a 1.8 m by 6.1 m (6 ft. by 20 ft.) loop cost the district $507.88, while a 1.8 m by 12.2 m (6 ft. by 40 ft.) replacement cost $885.13. One way to approximate the cost of failures is to use the district's best estimate of the failure rate and use this rate over some future period. For the two interchanges discussed above, this analysis assumes between 10 percent and 20 percent of the loops will fail within a 10 year time frame, and that they are replaced as they fail. For either of the interchanges discussed above, this equates to approximately 4 loops up to as many as 8 loops to be replaced. Using the cost of a 1.8 m by 6.1 m (6 ft. by 20 ft.) loop as the basis of the estimate, the low estimate would be 4 x $507.88 and the high estimate would be 8 x $507.88. If this is converted to a present worth, the cost of loop replacements in today's dollars is amortized over the 10 year period at an assumed 3 percent interest rate, this means an annual cost of from $300 to $600. This analysis assumes that the salvage value of each detector type will be very similar and therefore will not contribute significantly to the decision process.

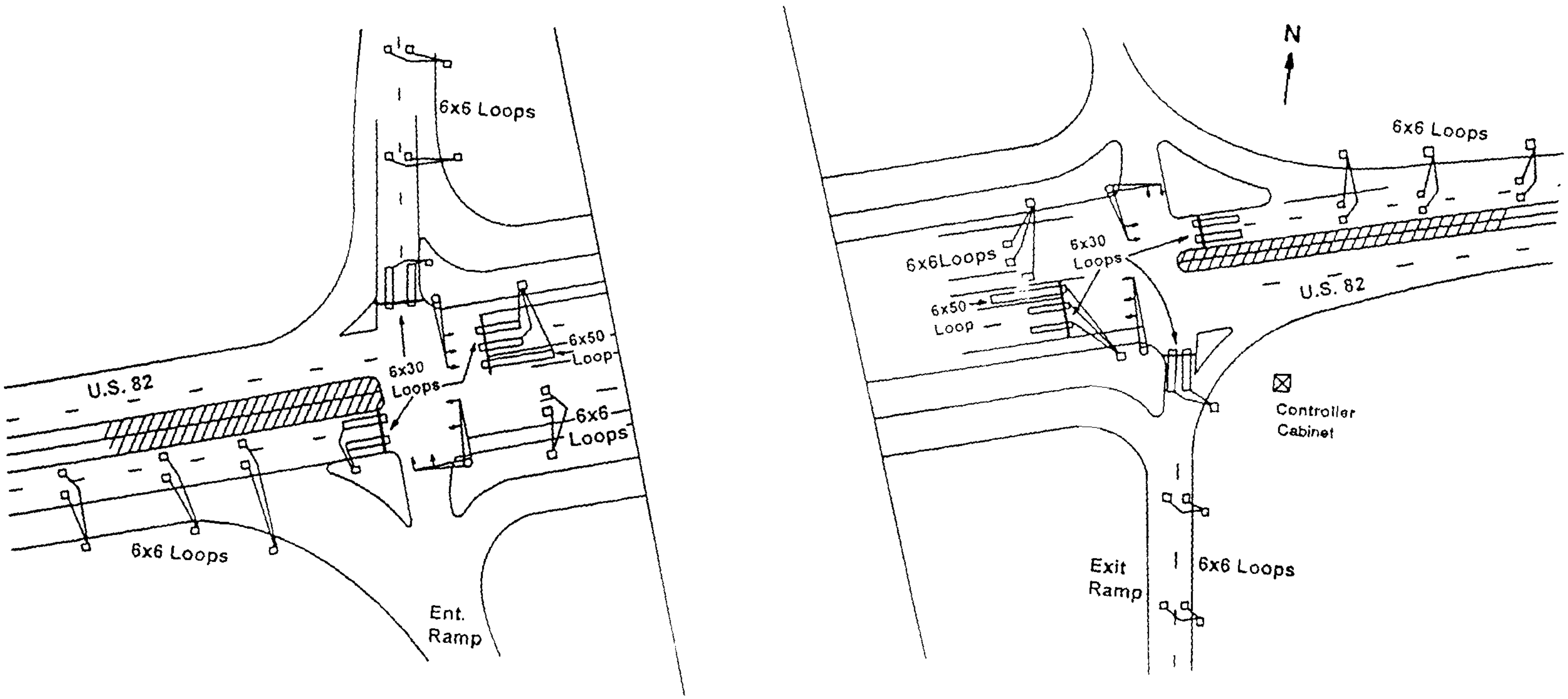

Figure 5-1. U.S. 82/Business 82 Interchange

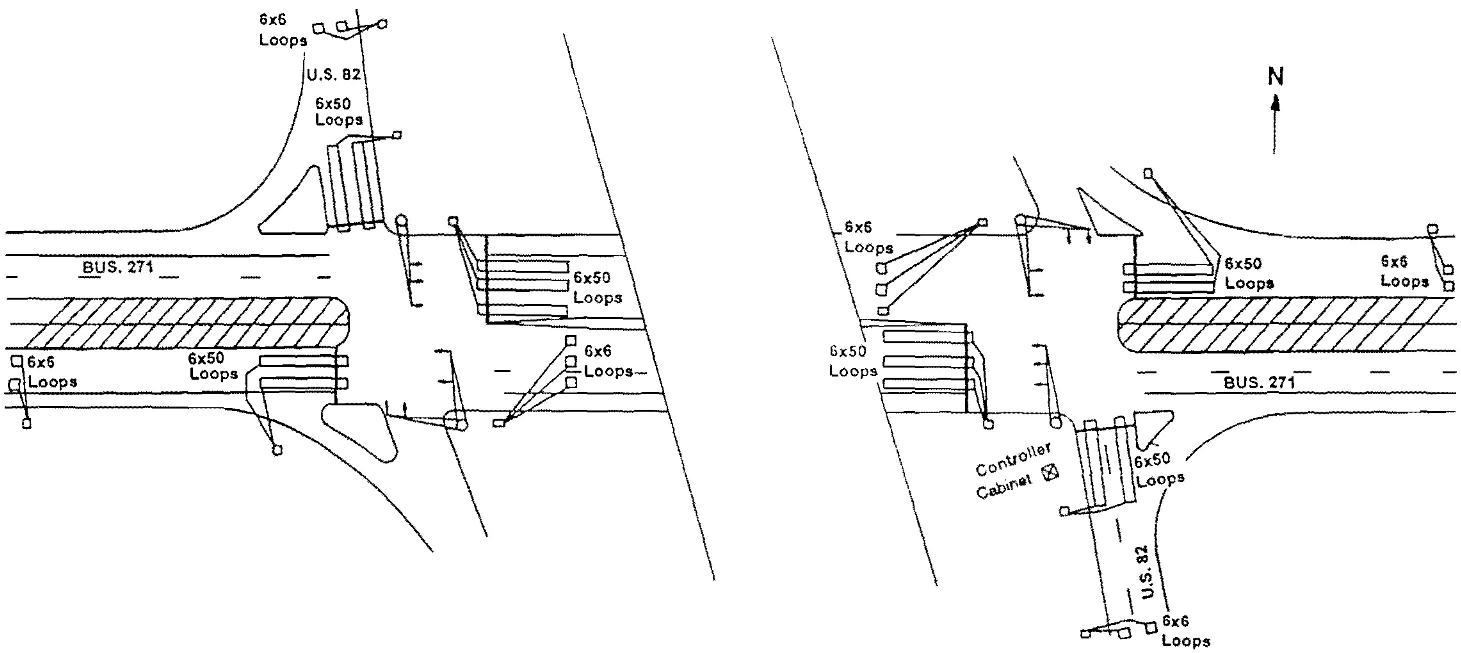

Figure 5-2. U.S. 82/U.S. 271 Interchange

Table 5-4. Inductive Loop Costs on Business 82 in Paris, Texas

Location: US 82 @ Business 82, Paris, Texas
Install 14 each 1.8 x 9.1 m (6 ft. x 30 ft.) loops
with 1.8 m (6 ft.) headers and
22 each 1.8 m x 1.8 m (6 ft. x 6 ft.) advance loops

Item Description	Labor	Material
Install conduit from pull box to pavement edge	$ 757.68	$ 41.40
Saw cuts in pavement - some asphalt, some concrete	10,550.25	
Install 50.8 mm (2-in.) RMC		
173.4 m (569 ft.) trench	4,899.09	1,140.00
138.1 m (453 ft.) bore	5,979.60	920.00
Install ground boxes 15 each	2,688.00	1,230.00
Loop wire in duct 1737.4 m (5,700 ft.)		570.00
Loop lead in (2-C) 1,645.9 m (5,400 ft.)	3,564.00	756.00
Loop Sealant 614.9 liters (650 qts.)		5,297.50
Sealing packs 12 each		46.08
Loop amps 12 each		870.00
Traffic control - 5 days @ $50/day by TxDOT (Two men for 2 hrs for setup/take down plus use of signs.)	250.00	
SUM	$28,688.62	$10,870.98

Table 5-5. Inductive Loop Costs at US 271 in Paris, Texas

Location: US 82 /US 271, Paris, Texas
Install 14 each 1.8 m x 15.2 m (6 ft. x 50 ft.) loops
with 1.8 m (6 ft.) headers and
14 each 1.8 m x 1.8 m (6 ft. x 6 ft.) advance loops

Item Description	Labor	Material
Install conduit from pull box to pavement edge	$ 964.32	$ 55.20
Saw cuts in pavement - some asphalt, some concrete	10,833.75	
Install 50.8 mm (2-in.) RMC		
125.7 m (412 ft.) trench	3,547.32	840.00
159.4 m (523 ft.) bore	6,903.60	1,060.00
Install ground boxes 11 each	1,971.20	902.00
Loop wire in duct 1,889.8 m (6,200 ft.)		620.00
Loop lead in (2-C) 1,432.6 m (4,700 ft.)	3,102.00	658.00
Loop Sealant 639.2 liter (670 qts.)		5,460.50
Sealing packs 12 each		46.08
Loop amps 12 each		870.00
Traffic control - 8 days @ $50/day by TxDOT (Two men for 2 hrs for setup/take down plus use of signs.)	400.00	
SUM	$27,722.19	$10,511.78

5.3 ILD COSTS ON FREEWAYS

Differences in costs of inductive loops on freeways is typically due to traffic control costs, longer distances between the loops and the cabinet, and different numbers of loops per location compared to intersections. Traffic control costs consist of both the cost to install and maintain traffic control devices as well as the delay to motorists during the loop installation or maintenance.

To compute user delay costs on freeways, the project staff used a computer program developed at the Texas Transportation Institute (TTI) called QUEWZ. This stands for Queue and User Cost Evaluation of Work Zones; the version used in this analysis was QUEWZ-92. It is a computerized version of commonly used manual methods for estimating queue lengths and additional road user costs resulting from work zone lane closures. The user inputs the time schedule and lane configuration of the work zone; the program simulates traffic flows through freeway segments both with and without a work zone lane closure in place. The model can be applied to freeway or multilane divided facilities with as many as six lanes in each direction, and it can analyze work zones with any number of lanes closed in either one or both directions. It can either evaluate road user costs or provide a lane closure schedule that summarizes the hours of the day when a given number of lanes can be closed without causing excessive queueing (defined by the user).

The diversion algorithm is used in conjunction with the road user cost output option. It estimates the volume of traffic that would divert from the freeway in response to work zone-related delays. Results are based on observations of work zone lane closures on urban freeways with continuous frontage roads in Texas. Queue lengths and delays tended to reach threshold levels soon after the lane closure was implemented and then remain near those threshold levels throughout the duration of the lane closure (*45*). It should be noted that both installation and repair of loops cause delays. Not all loop repairs require work on the pavement, although a high percentage of them do.

Table 5-6. Costs of Replacement Loops in the Paris, Texas District

Item Description	Labor	Material	Total
1.8 m x 6.1 m (6 ft. x 20 ft.) loop with powerhead Traffic control (one day)	$ 283.50 50.00	$174.38	$507.88
1.8 m x 12.2 m (6 ft. x 40 ft.) loop with powerhead Traffic control (one day)	$526.50 50.00	$308.63	$885.13

5.3.1 El Paso District

The cost for labor per loop is $150 to $200; the materials cost per loop is $200 to $300. The cost of traffic control is $395 for one lane closure and $695 for two-lane closure. If loops are replaced properly from the outset, they may last 10 to 15 years. It is very important to coordinate loop installation with utility companies. Otherwise, the utility company will damage the loops with each utility construction activity.

5.3.2 Ft. Worth District

Loop replacement costs for freeways are a few years old and are based on requests for bids to repair failed loops. Three companies submitted preliminary cost estimates, all on a different basis as follows. 1) $8 per 3.0 m (10-ft.) of saw cut, not including traffic control; 2) $350 per 1.8 m by 1.8 m (6 ft. by 6 ft.) loop, based on 10 loops; and 3) $1,200 to $1,500 per lane plus $1,500 per day per lane closure based on 10 loops. District personnel stated that lane closure costs for two lanes would be twice the $1,500 value. The district only closes lanes during the off-peak period from 9 am to 3 pm. Apparently, TxDOT district personnel currently perform loop repairs although they are not comfortable placing their employees on the roadway. However, they did not know the maintenance costs associated with loops. They are very interested in purchasing non-intrusive detectors to replace loops. Their experience has been that loops are not very reliable, and their reliability seems to change with the weather. The District experiences pavement failures near loops then pavement repairs cause loop problems.

5.3.3 Houston District

Table 5-7 is a list of costs associated with freeway inductive loops provided by the Houston district in June 1996. One comment from the district related to this bid was that the contractor is fairly new so his bid may be on the low side. These cost elements relate to both loop installation and maintenance. The quoted replacement costs for loop wire in concrete include materials cost for wire, sealant, and so forth. This cost per unit of saw cut is lower than for the initial installation because the contractor uses a thinner blade and simply cleans out the old saw cuts. Cutting is much faster than cutting concrete for the first time. Therefore, the linear footage cost includes both the removal of the old loop and installation of the new loop wire and sealant. This typically does not require installing new leads from the pull box to the controller.

An important difference in the installation procedure between Houston and some other districts is that Houston uses a product called "detecta-duct" in the saw cut. It requires the cut to be wider, possibly increasing the price. Also, durability should be increased, reducing the life cycle cost of these sensors. If a loop fails in asphalt, the Houston district requires a new loop in addition to the old one.

A typical layout for pull boxes on freeways is one small pull box beside the loops, then one close to the controller cabinet. Their typical maximum distance between pull boxes is 91.5 to 122.0 m (300 to 400 ft.) to make the wire pulls easier. They use two loops per lane for speed detection on freeway mainlanes and also on frontage roads as part of their ramp metering setup. The bid item is based on the length of saw cut, so there are only two wires in the cut except in the loop itself where there are three. This simplifies the bid process -- there is only a bid for two separate items: length of saw cut and length of conduit.

As for the cost of traffic control, the prime contractor often subcontracts this item and marks it up by perhaps 15 percent. In the past, the Houston district required selected lane closures on

Sunday mornings. However, they recently changed to lane closures at night. In some cases, they close the freeway and route traffic onto frontage roads. This factor creates a significant cost difference between freeways and intersections.

In providing the costs of loop repair, the district spokesman stated that the cost estimates do not include detector amplifier costs because these are kept separate. The district does not want loop replacement crews inside the cabinet simply because work inside the cabinet requires different knowledge and skills than replacing loops or pull boxes. Also, the district did not provide loop amplifier costs because it is in the process of replacing its shelf-mount units with rack-mount units (with two channels). The analysis below assumed component costs similar to those in Ft. Worth for intersections.

Table 5-7. Freeway Inductive Loop Costs from the Houston District

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

Table 5-8 summarizes estimated installation and replacement inductive loop costs for one direction of a six-lane freeway which has concrete pavement, 3.05 m (10 ft.) paved shoulders, 3.66 m (12 ft.) lanes, requiring two pull boxes 45.72 m (150 ft.) apart, with one pull box near the loop site

Table 5-8. Cost of Installation and Replacement of Freeway Loops

INSTALLATION COST ITEM (Six Loops)	COST
Saw cut: 49 ft x 6 x $3.50/ft [a]	$ 1,029.00
Loop wire: 150 x 6 x $0.14 [a]	126.00
Lead in from shoulder to pull box:	
Conduit: 12 ft x $6/ft	72.00
Wire (included above)	
Pull boxes ($200 ea. x 2)	400.00
Lead in from pull box to pull box	
Conduit: 150 ft x $6/ft	900.00
Wire (2 conductor shielded): 150 x 6 x 2 x $0.15/ft	270.00
Pull box to cabinet: 15 x 6 x $0.15	13.50
Loop detector:	540.00
Traffic control	1,500.00
Minimum motorist delay [b]	1,000.00
TOTAL INSTALLATION COST	$ 5,850.50
Installation cost per loop	$ 975.08
REPAIR COST ITEM (per loop)	
Saw cut: 49 ft x $3.50/ft	$ 171.50
Loop wire: n/a	
Pull boxes: n/a	
Lead in from shoulder to pull box:	
Conduit: n/a	
Wire (included above)	
Lead in from pull box to pull box	
Conduit: n/a	
Wire (2 conductor shielded): n/a	
Pull box to cabinet: n/a	
Loop detector: n/a	
Traffic control	1,000.00
Minimum motorist delay [c]	200.00
TOTAL REPAIR COST (per loop)	$1,371.50

1 meter = 3.28 feet

[a] Note: If power header is used, add additional saw cut and loop wire.
[b] Motorist delay for installation varied from $1,000 to $15,000, depending on the time period.
[c] Motorist delay for repair varied from $200 to almost $15,000 depending on the time period.

and one near the cabinet. Each lane has two 1.8 m by 1.8 m (6 ft. by 6 ft.) loops spaced 3.66 m (12 ft.) apart. The materials required are for the second lane from the shoulder. For ease of comparison, the installation analysis calculates loop costs for all three lanes simply because a video system could replace this system of loops with one camera. For simplicity of calculation, the analysis multiplies the length of materials for a loop in the center lane by a factor of six to determine totals.

Motorist delay calculations required several assumptions. Recent hourly traffic counts from U.S. 59 provided the basis of delay costs. Because the Houston district now requires lane closures at night, delay, and thus delay costs, are much less than during the daytime. However, motorist delay, even at night, is highly sensitive to the actual hours of operations and the number of lanes remaining open. Two traffic control options are available: a) route all traffic onto the frontage roads (assuming they are continuous) and b) keep a minimum of one freeway lane open through the work zone. The latter option is chosen. The QUEWZ program, used to determine road user costs, assumed 8 percent trucks and a work zone length of 304.8 m (1,000 ft.) The least amount of motorist delay for a six-hour work period (no interruptions) for installing loops in all three lanes, maintaining one lane open continuously, occurred if the work began at midnight and ended at 6:00 a.m. The delay costs totaled approximately $1,000 for this time period. In comparison, if the work began at 9:00 p.m. and ended at 3:00 a.m., delay costs totaled approximately $15,000. The difference is due to greater traffic volume earlier in the evening. Likewise, for a one-lane closure to repair a loop, delay costs varied from practically zero to almost $15,000. One reason for a one-lane repair appearing to cause delay costs that were similar to a full installation is the assumption that a loop repair in the center lane would require closure of both the inside lane and the center lane. Under this scenario, lane closure would begin at 9:00 p.m., work would begin at 10:00 p.m., and lanes would be reopened at midnight. Maintaining two lanes open (e.g., loop repair on the inside or outside lane) during this same time period and same traffic volumes resulted in delay costs of only $200.

Using minimum motorist delay costs, the initial cost of six inductive loops on a freeway would be $5,850 or $975 per loop. Repair cost, assuming minimum delay cost ($200) was approximated at $1,371 per loop repair. Using a failure rate similar to that found at intersections, there would be perhaps one of these six loops needing replacement within 10 years. At the same assumed 3 percent rate as used elsewhere, this life-cycle loop cost equates to a 10-year present worth of $7,692.

5.4 VIDEO DETECTION COSTS

Detection using video image processing systems provides a flexible format for either intersections or freeways. Image processors typically accommodate more than one camera, and each camera's viewing area includes multiple detection zones. Therefore, video is most cost-effective where many detectors are needed — such as at intersections.

5.4.1 Initial Cost

A straightforward comparison of video costs versus inductive loop costs at signalized intersections is available by using information from the Paris district. A video image processing system to provide the same level of detection at either Paris interchange would require one processor and six cameras, plus the cabling and hardware to install the system. The cost estimate assumes that a cabinet exists for the video processor, and that poles exist at the intersections for mounting cameras, so costs were not increased these items. Costs of a processor and six cameras are approximately $24,000 and $9,000, respectively. It should be noted that some processors are available at lower cost, but they either only accommodate four cameras or they do not have the desired functionality. Ancillary equipment such as mounting hardware and cabling was estimated at approximately $500 per camera. Installation costs for cameras, processor, and other hardware were estimated at $300 for each of the two intersections. This assumes one bucket truck ($60/day) and two technicians ($15/hr) for eight hours per intersection. The total initial cost for video systems at each of the two interchanges was $36,300.

Based on the analysis above, the initial cost of a video system is slightly less than the initial cost of loops. However, one must consider motorist delay during installation of loops, which is usually negligible for video. District personnel in Paris indicated that during the installation of the loops there was some minor delay incurred by motorists but it was not severe. Traffic control costs would also be higher for most loop installations than that estimated by district personnel in Paris ($50 per day). Both of these items increase the difference in costs between loops and video, in favor of video. Maintenance costs of both systems must also be considered.

5.4.2 Video Maintenance Cost

Video maintenance costs are not well documented, for one reason because they are relatively new to the arena of vehicle detection. To be realistic about their life cycle cost, however, one must consider the available evidence, even though it may be limited. Researchers evaluated costs based on records kept by the Road Commission of Oakland County, Michigan, which kept records on their FAST-TRAC (Faster and Safer Travel - Traffic Routing and Advanced Control) system for part of the time since beginning installation in 1991. During this time period, there were failures in cameras and in processors, as well as less expensive problems such as short-circuits and other maintenance problems. It should be noted that other ITS elements of the FAST-TRAC system, which integrated Advanced Traffic Management Systems (ATMS) with Advanced Traveler Information Systems (ATIS), were excluded from this cost analysis.

Detailed information from the Road Commission of Oakland County, Michigan (RCOC) based on recent actual monthly expenditures provided useful information in determining the life cycle costs of these Autoscope™ systems. The information provided in Tables 5-9 through 5-12, and summarized in Table 5-13 represents a total of 166 Autoscope™ controllers and 560 cameras installed by the RCOC. These are actual cost data for January through August 1995 for four suburban areas near Detroit, Michigan. The FAST-TRAC program experienced failure in two of its initial 22 Autoscope™ units during their first nine months of operation. If spread over the balance of the units purchased, this results in a preliminary calculated mean-time-before-failure (MTBF) of 72,300 hours (8.2 years). These early tests included inclement weather such as rain, fog, and snow.

Camera manufacturers claimed that the MTBF for their cameras was 427,380 hours (48.8 years) or 180,354 hours (20.6 years at the 90 percent confidence level. Experience of the FAST-TRAC program indicated failure of one of 67 cameras in the first 18 months of operation for the first 22 Autoscope™ systems installed. This equates to one failure in 808,000 hours (92 years) of combined operation. *(44)*

Table 5-13 summarizes monthly and yearly unit costs based on information provided by RCOC. These are costs of labor, fringe benefits, and equipment costs (e.g. repair truck and radio). Because the Autoscope™ systems were under warranty, cost of repair parts and new replacement units were paid for by the manufacturer or distributor. Therefore, for older units whose warranty period has expired, the maintenance cost could be higher. Based on the first eight months of 1995, the monthly average cost per camera for maintenance ranged from a low of $3.07 to a high of $15.47; for Autoscope™ units, the range was $16.61 to $29.61. Using the mean values, one could anticipate spending approximately $9.27 per month on camera maintenance and $23.11 per month on other components. Therefore, for a six-camera intersection setup as needed at each of the two Paris, Texas interchanges, the maintenance cost of cameras plus processor could range from a low of $35.03 to a high of $122.43 per month per interchange. Perhaps with continued use resulting in greater user familiarity, and enhancements to improve longevity, these maintenance costs will decline.

5.5 COMPARISON OF ILD AND VIDEO DETECTION COSTS

Even though the information available in the literature on detector costs was limited, it provided useful comparisons for Texas costs. For example, Reference *(44)* indicated that the installation cost of 1.8 m by 1.8m (6 ft by 6 ft) inductive loops in Minnesota was $560, which compares favorably with costs in Texas. However, their traffic control cost of $40 per loop is too low in comparison. Perhaps the largest difference in their assessment of loop installation costs and the Texas costs was in motorist delay. In the Reference *(44)*, case, the installation was on a freeway where one of the two available lanes was closed for two hours to install loops. According to their simulation program, this resulted in delay and extra fuel costs to motorists of $164,000. Delays to motorists at signalized intersections are expected to be much less than this number suggests, but this will be verified as part of ongoing research.

In references *(41)* and *(42)*, component costs were higher than those found in TxDOT practice. Their $49.20 per meter ($15 per ft) for saw cuts was approximately four times the unit cost in Texas; their cost for loop amplifiers was $400, whereas the cost in Texas is under $100. Other cost quotes in these references included other components, making an equal comparison impossible.

Table 5-9. Autoscope™ Maintenance Costs for 1995 in Pontiac, Michigan

13 Controllers, 44 Cameras

Month	Controller	Camera	Monthly Total	YTD Cum. Total
January	399.48	.00	399.48	399.48
February	302.97	.00	302.97	702.45
March	963.43	354.60	1318.03	2020.48
April	434.21	.00	434.21	2454.69
May	.00	.00	.00	2454.69
June	545.40	.00	545.40	3000.09
July	434.08	428.36	862.44	3862.53
August	.00	473.95	473.95	4336.48
YTD Total	3079.57	1256.91	4336.48	
Monthly Ave.	384.94	157.11	542.05	

[a] Costs of monthly labor, fringe benefits, and equipment costs (truck, boom, radio). Equipment costs covered by manufacturer/distributor.

Table 5-10. Autoscope™ Maintenance Costs for 1995 in Auburn Hills, Michigan [a]

41 Controllers, 139 Cameras

Month	Controller	Camera	Monthly Total	YTD Cum. Total
January	1662.98	403.72	2066.70	2066.70
February	839.19	.00	839.19	2905.89
March	1306.18	2289.01	3595.19	6501.08
April	99.87	.00	99.87	6600.95
May	305.61	249.70	555.31	7156.26
June	951.95	149.83	1101.78	8258.04
July	927.64	323.88	1251.52	9509.56
August	853.49	.00	853.49	10363.05
YTD Total	6946.91	3416.14	10363.05	
Monthly Ave.	868.36	427.01	1295.38	

[a] Costs of monthly labor, fringe benefits, and equipment costs (truck, boom, radio). Equipment costs covered by manufacturer/distributor.

Table 5-11. Autoscope™ Maintenance Costs for 1995 in Rochester Hills, Michigan [a]

43 Controllers, 155 Cameras

Month	Controller	Camera	Monthly Total	YTD Cum. Total
January	401.72	2442.06	2843.78	2843.78
February	1543.88	403.96	1947.84	4791.62
March	537.66	2069.58	2607.24	7398.86
April	126.25	88.65	214.9	7613.76
May	149.83	198.79	348.62	7962.38
June	299.61	.00	299.61	8261.99
July	2653.23	.00	2653.23	10915.22
August	518.83	667.67	1186.5	12101.72
YTD Total	5712.18	5203.04	10915.22	
Monthly Ave.	714.02	650.38	1364.40	

[a] Costs of monthly labor, fringe benefits, and equipment costs (truck, boom, radio). Equipment costs covered by manufacturer/distributor.

Table 5-12. Autoscope™ Maintenance Costs for 1995 in Troy, Michigan [a]

69 Controllers, 222 Cameras

Month	Controller	Camera	Monthly Total	YTD Cum. Total
January	3905.03	7198.78	11103.81	11103.81
February	504.98	504.98	1009.96	12113.77
March	899.64	7548.49	8448.13	20561.90
April	1623.33	3321.98	4945.31	25507.21
May	2286.83	3364.34	5651.17	31158.38
June	492.84	633.82	1126.66	32285.04
July	1866.38	1879.63	3746.01	36031.05
August	2217.41	3017.04	5234.45	41265.50
YTD Total	13796.44	27469.06	41265.50	
Monthly Ave.	1724.55	3433.63	5158.18	

[a] Costs of monthly labor, fringe benefits, and equipment costs (truck, boom, radio). Equipment costs covered by manufacturer/distributor.

Table 5-13. Summary of All RCOC Systems [a]

System	Mode	Total Monthly	Total Yearly	Monthly Cost Per Unit
Pontiac 13 controllers 44 cameras	Camera	157.11	1885.32	3.57
	Autoscope™	384.94	4619.28	29.61
	Total	542.05	6504.6	
Auburn Hills 41 controllers 139 cameras	Camera	427.01	5124.12	3.07
	Autoscope™	868.36	10420.32	21.18
	Total	1295.38	15544.56	
Rochester Hills 43 controllers 155 cameras	Camera	650.38	7804.56	4.20
	Autoscope™	714.02	8568.24	16.61
	Total	1364.40	16372.8	
Troy 69 controllers 222 cameras	Camera	3433.63	41203.56	15.47
	Autoscope™	1724.55	20694.6	24.99
	Total	5158.18	61898.16	
Total for All Systems 166 controllers 560 cameras	Camera	4668.13	56017.56	8.34
	Autoscope™	3691.87	44302.44	22.24
	Total	8360.00	100320.00	

[a] Costs of monthly labor, fringe benefits, and equipment costs (truck, boom, radio). Equipment costs covered by manufacturer/distributor.

Comparing the cost of installing loops at the two interchanges in Paris, Texas with the initial cost of video detection for the same interchanges indicates similar costs. The Paris District documented the total cost of loop installation at the US 82/Business 82 interchange at $39,560. For the US 82/US 271 interchange, the installation cost was $38,234. If motorist delay and excess fuel consumption are considered, although modest, the cost would be even more. The initial cost of a video system for either interchange would be $36,450. Therefore, based on installation cost only, video appears to be less expensive.

5.5.1 Signalized Intersections

For the Paris, Texas intersections, assuming 10 to 20 percent failures over a 10-year time period, the annual cost for inductive loop detectors is between $300 and $600. Based on video maintenance data from Michigan, monthly maintenance on cameras and processors are between $35 and $122 per month. On a yearly basis, this is $420 to $1,469. Using a present worth analysis and assuming a 3 percent annual interest rate, today's life cycle cost of operating a video system for either of these two intersections would be between $40,036 and $48,982. Salvage value for each system is assumed to be the same at the end of 10 years.

A similar present worth analysis of the loop system indicates that its maintenance cost range of $300 to $600 per year, being less than the high end of annual maintenance cost for video, makes loops appear more attractive than they did using only the installation cost comparison. The present worth of installing and operating a loop system for 10 years (excluding any motorist delay or excess fuel consumption during installation) would be between $42,119 and $44,678 for the US 82/Business 82 interchange. The other interchange would be slightly less.

Other items that might change the outcome of the cost comparison are motorist delay, flexibility of video systems, and accidents caused by lane closures. Motorist delay could be a significant cost contribution at high volume intersections where the present worth of both systems is very similar otherwise. Delay costs due to installing or maintaining loops could significantly add to the attractiveness of video image processing systems over inductive loops in cases where many loops can be replaced by one camera. No attempt was made to quantify the additional flexibility of video or the possible increase in accidents caused by inductive loop installations. However, both factors increase the relative attractiveness of video.

5.5.2 Freeways

Using minimum motorist delay costs, the initial cost of six inductive loops on a freeway in Houston would be $5,850 or $975 per loop. Repair cost, assuming minimum delay cost ($200) was approximated at $1,371 per loop repair. Using a failure rate similar to that found at intersections, there would be perhaps one of these six loops needing replacement within 10 years. At the same assumed 3 percent rate as used elsewhere, this life-cycle loop cost equates to a 10-year present worth of $7,692.

Costs of a processor and two cameras are approximately $18,000 and $3,000, respectively. Ancillary equipment such as mounting hardware and cabling was estimated at approximately $500 per camera. Installation costs for cameras, processor, and other hardware were estimated at $300. This assumes one bucket truck ($60/day) and two technicians ($15/hour) for eight hours. The total initial cost for video systems at each of the two interchanges was $21,800. In order to make an equal comparison with inductive loop costs above, this total cost per location is divided in half. Thus, the initial cost of video to replace six loops would be $10,900. To this must be added the maintenance cost for a 10-year period. This is $9.27 per month per camera and $23.11 per month for other components, for a total one-direction cost of $249.90 per year. Converting to a present worth brings the total to $13,032. This is considerably more expensive than the loop system, assuming similar salvage values for both systems.

6.0 SUMMARY AND CONCLUSIONS

This study evaluated an Autoscope™ 2004 trip-wire video image processing system's ability to accurately count vehicles and detect vehicle speeds within a freeway grid 122.0 m (400 ft.) long by six lanes wide. Speed accuracy was determined based on comparisons with radar speeds. The study also evaluated the influence of other vehicles in adjacent lanes on the detection of passenger cars (effects of occlusion). A two-car pair traveled in lane 6 without the presence of other passenger cars in lane 5. The same two-car pair traveled in lane 6 with another two-car pair traveling alongside in lane 5. The analysis determined if influences from the two-car pair in lane 5 were significant. Study variables, including camera height and lane location, yielded information on the effects each has on detection location. The statistical analysis determined whether the values were significantly different.

This study primarily utilized passenger cars during midday, although a smaller sample of data used a single-unit truck with three passenger cars, as well as some non-midday tests. Lighting conditions for non-midday periods included darkness and low sun angle during the late evening and early morning. The pavement condition was always dry with the exception of some limited night testing where a water truck kept the pavement wet. Study staff were unable to complete the inclement weather tests due to the scarcity of intense rain or fog.

6.1 SUMMARY

6.1.1 Detection Distance Analysis

For the 32 km/h (20 mph) passenger car speed, several findings became evident. First, each camera height was significantly different from other camera heights. However, analyzing the individual camera height-travel lane data sets revealed that some camera height-travel lane data were within the same statistical grouping. While the 15.1 m (49 ft. - 6 in.) camera height generally detected (counted) two passenger cars farther upstream than the 12.2 m (40 ft.) or 9.1 m (30 ft.) camera heights in this study, future site limitations may preclude camera mounting above a preconceived height. Statistical groupings, the imaging system's detection range information, and camera offset information can assist the designer in optimizing the field of view for site specific conditions.

Another general finding was that the detection distance increased as the lane offset increased. This phenomenon was due to the occlusion effects of the first passenger car. The vertical occlusion or the ability of the first vehicle to "hide" the second passenger car was less in lanes farther from the camera. It should be noted that this study analyzed detection distance based primarily on passenger cars. As expected, occlusion was worse when a passenger car followed a truck than when it followed another passenger car. The fixed 1.5 second headway provided a sufficient gap at speeds of 72 km/h (45 mph) and 88 km/h (55 mph) for the Autoscope™ system to consistently detect (count) two passenger cars at a distance of 121.9 m (400 ft.) away from the camera. These results indicate that detection distance limit is located at a distance greater than 121.9 m (400 ft.) upstream from the camera. Figure 6-1 shows these relative distances for nominal speeds of 32 km/h (20 mph), with the exception of the detection distance associated with the 12.2 m (40 ft.) camera height in lane 6 that was thought to be biased. The detection range for passenger car speeds of 72 km/h (45 mph) and 88 km/h (55 mph) exceeded 121.9 m (400 ft.) in all cases, so exact distances were unavailable. It should be noted that detections (counts) on an actual freeway using the same camera offsets, especially with heavy traffic volumes, would be expected to yield different results. Count accuracies on lanes farther from the camera would likely be substantially worse than those closer to the camera due primarily to the effects of vehicle occlusion in lanes closer to the camera.

6.1.2 Passenger Car Speed Comparisons

The hypothesis that vehicle speeds determined by the Autoscope™ system and those determined by radar were the same was rejected. Comparing the *unadjusted* mean speed values from speeds determined by the Autoscope™ system and the mean radar speed values revealed a fairly constant percent difference for a given camera height, regardless of passenger car speed. The percent differences in passenger car speed were from approximately 23 percent for a camera height of 9.1 m (30 ft.), approximately 16 percent for a camera height of 12.2 m (40 ft.), and approximately 15 percent for a camera height of 15.1 m (49 ft. - 6 in.)

One possible source of error lies in how the Autoscope™ system determines the vehicle signature and monitors the vehicle through the detection zone. Another error source influencing its speed accuracy is the manner in which the Autoscope™ system establishes the speed trap. The speed trap dimensions are dependent on the pixel resolution of the processed video image.

Applying the Autoscope™ calculation adjustment factor to the Autoscope™ passenger car speeds reduced the difference between Autoscope™ and radar speeds. However, the *adjusted* Autoscope™ speeds were still statistically different in some comparisons. The percent difference between the mean speed values obtained by radar and the adjusted Autoscope™ mean speed values indicated only a slight difference (less than one percent) in speed determination between the 12.2 m (40 ft.) camera height and the 15.1 m (49 ft. - 6 in.) camera height, when all travel lane speed data were combined.

6.1.3 Detection Location Influences from Passenger Cars in Adjacent Lanes

Some statistical comparisons resulted in rejection of the null hypothesis that vehicles in lane 5 influenced the system's detection ability in lane 6. Observing the videotape revealed that passenger cars in lane 5 did not completely hide lane 6 passenger cars. There was always a sufficient portion of the passenger car in lane 6 visible to pass through the detection zone in travel lane 6. Thus, the variability of the data is attributed to factors other than vehicle influences from travel lane 5. These factors include: reflections from the vehicle, electronic "noise," shadows,

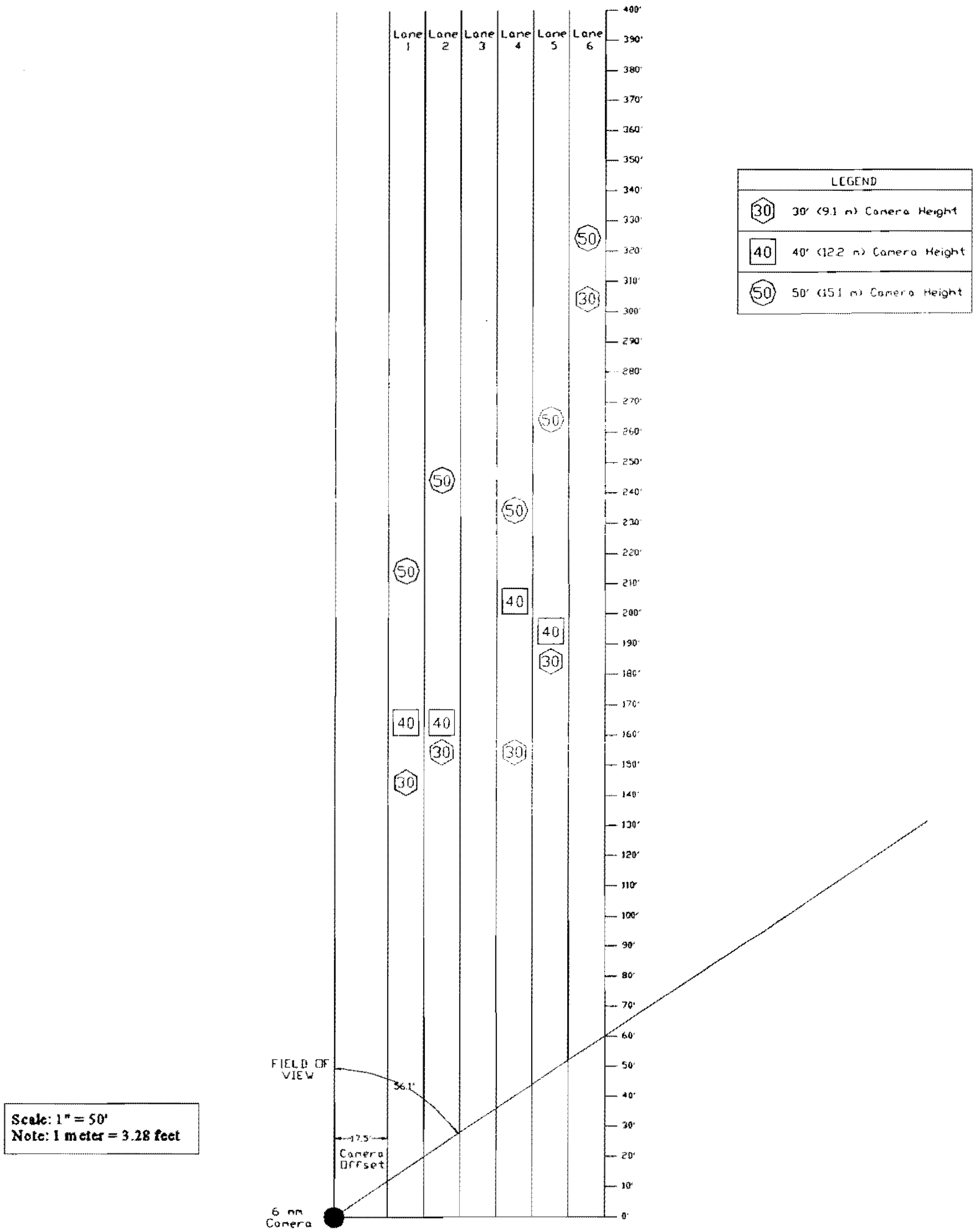

Figure 6-1. Midday Detection Range at 32 km/h (20 mph)

or cloud cover. Larger vehicles in the foreground will have an even greater propensity to hide smaller vehicles from view, perhaps resulting in a different outcome. The finding that accurate vehicle counts generally occurred farther upstream of the camera location in lanes farther from the camera must be interpreted carefully. On a high volume freeway, count accuracy is likely to decrease significantly in lanes 5 and 6 due to occlusion by vehicles in the near lanes. Based on interviews with both practitioners and researchers, a four is the maximum number of adjacent freeway lanes that can be "accurately" counted with one camera mounted not more than 15 feet off the roadway. Count accuracy in heavy flows will be reduced in lanes farther from the camera.

6.1.4 Cost Comparisons Between Inductive Loop Detection and Video Detection

The cost analysis of video image processing systems and inductive loop detectors *at intersections* indicates similar costs for the two systems when only installation and maintenance costs are considered. The compared costs of video include labor, fringe benefits, and equipment costs (e.g., repair truck and radio), and exclude repair parts and replacement units since video systems were still under warranty. The maintenance cost would probably be higher on older units. Based on these stipulations, agencies should anticipate spending a mean value of approximately $9.27 per month on camera maintenance and $23.11 per month on processor maintenance. For a six-camera intersection setup similar to the Paris, Texas example, the maintenance cost of cameras plus processor could range from a low of $35.03 to a high of $122.43 per month per interchange. Today's life cycle cost of operating a video system for either of these two interchanges for a time period of 10 years would be between $40,036 and $48,982. The present worth of installing and operating a loop system for 10 years would be between $42,119 and $44,678. Neither analysis considered salvage value as a variable, but both systems are assumed to have similar lengths of useful life beyond the 10-year time frame. Variables that must still be evaluated for inductive loops are motorist delay and excess fuel consumption during installation or repair. This additional cost for inductive loops could increase the life-cycle costs of loops such that they are considerably more expensive than video detection.

On *freeways*, there are typically fewer inductive loops to be replaced by each video camera, often resulting in lower life cycle costs for inductive loops. Chapter 5 contains an investigation of inductive loop costs for one direction of a six-lane freeway in Houston which has concrete pavement, 3.05 m (10 ft.) paved shoulders, 3.66 m (12 ft.) lanes, and pull boxes. Each lane has two 1.8 m by 1.8 m (6 ft. by 6 ft.) loops spaced 3.66 m (12 ft.) apart. Recent hourly traffic counts from U.S. 59 provided the basis of delay costs. Motorist delay, even at night, is highly sensitive to the actual hours of operations and the number of lanes remaining open. Two traffic control options are available: a) route all traffic onto the frontage roads (assuming they are continuous) and b) keep a minimum of one freeway lane open through the work zone. The latter option was chosen. QUEWZ program output indicated that for both installation and repairs, the cost of motorist delay could vary from almost zero (lowest traffic volume) to approximately $15,000 (higher traffic volume). Using minimum motorist delay costs and other assumptions discussed in Chapter 5, the initial cost of six inductive loops on a freeway would be $5,850 or $975 per loop. Repair cost, assuming minimum delay cost ($200) was approximated at $1,371 per loop repair. Using a failure rate similar to that found at intersections, there would be perhaps one of these six loops that needs replacement within 10 years. At the same assumed 3 percent rate as used elsewhere, this life-cycle loop cost equates to a 10-year present worth of $7,692.

Costs of a replacement video system would consist of a processor and two cameras, costing approximately $18,000 and $3,000, respectively. Ancillary equipment such as mounting hardware and cabling was estimated at approximately $500 per camera. Installation costs for cameras, processor, and other hardware were estimated at $300. The total life-cycle cost of a video system at a freeway location to monitor one direction of traffic would be $13,032. This is considerably more expensive than the loop system, assuming similar salvage values for both systems.

6.2 CONCLUSIONS

6.2.1 Midday Tests

Even under optimum conditions, Autoscope™ speeds were significantly different from radar speeds, based on the paired *t* test. A freeway operating agency could apply an appropriate correction (it is always a downward correction in speed) and be within 11 percent of the actual speed for passenger cars. Truck speed errors would be greater because one factor would probably be used, the correction for passenger cars. Adjusted video speeds are still almost always higher than radar speeds, suggesting that perhaps a slightly higher correction might be used than that applied in this report. The maximum variation between adjusted Autoscope™ speeds and radar at 32 km/h (20 mph) was 7 percent, and at 72 km/h (45 mph) and 89 km/h (55 mph), it was within 11 percent. The percent difference between the mean radar gun speed and the mean *adjusted* Autoscope™ speed suggested a modest speed accuracy improvement of 1.5 percent by increasing the camera height from 9.1 m to 12.2 m (30 ft to 40 ft).

A commonly stated advantage of video detection over inductive loops is its ability to directly measure density (as a measure of level of service). However, with a 6 mm lens, the Autoscope™ system would only be able to monitor a few hundred feet of freeway. The actual distance needs to be determined at high speeds to determine how much greater than 122.0 m (400 ft) the actual detection distance is. If the distance is 182.88 m (600 ft.), for example, and retaining 1.5 second headways, a freeway speed of 97 km/h (60 mph) represents less than five passenger cars. This distance is still very short for measuring density.

Midday tests of occlusion indicated some statistical difference when passenger cars traveled in the adjacent lane closer to the camera. However, in most cases, passenger cars in lane 5 did not significantly influence the video image processing system's ability to accurately detect passenger cars in lane 6. The authors suspect factors other than vehicle interference to be the cause of detected differences. Image shifting, vehicle reflections, clouds, shadows or electronic "noise" interference could have contributed to variations in the system's ability to detect passenger cars in travel lane 6. Detection could occur when the car passed through only a portion of the detection zone. The detector size, length and width could also vary to further optimize the detector location. Varying the detector size and location minimized interference of passenger cars in adjacent lanes. Higher camera heights increased the flexibility of detector placement.

6.2.2 Non-Midday Tests

The Autoscope™ detects headlights at night versus detecting the body of the vehicle during daylight. One positive result was vehicles being detected at night at greater distances at the same camera height and vehicle speed as compared to daylight. Based on observations during video replay and watching the detectors, the difference is probably due to the drastic change in pixels from the vehicle headlights compared to the daylight detection method. The night tests generally produced more accurate speeds from lanes farther from the camera than closer lanes. However, speed accuracy at night is less than daylight accuracy.

Results of sunrise tests indicate little or no effect of a low sun angle on system operations. However, it should be noted that haze significantly reduced the sun's intensity on both mornings when testing occurred. Detections occurred sooner in occlusion tests than in tests without occlusion. Headlight activity had little or no effect on detections or speed accuracies at sunrise.

Testing with a large truck resulted in mixed results. There were no accurate data available in lanes 1 and 2 for evaluating occlusion by the truck either at night or during the daytime at 32 km/h (20 mph) and 28 km/h (45 mph). No 88 km/h (55 mph) tests were conducted with the truck. Daylight tests in lanes 5 and 6 resulted in accurate counts at 122.0 m (400 ft.) at 28 km/h (45 mph) but only because the top of the truck (in lane 5) was counted instead of the car in lane 6. Night tests detected only one vehicle in each lane, perhaps due to the amount of glare generated by both sets of headlights, reflections of car headlights on the truck, or short headways. Additional testing should be done with a truck closer to the camera (e.g., in lanes 1 and 2). Careful observation of the video replay indicated that the detector did not clear until all four vehicles were past. Insufficient data exist for determining a detection range from these truck runs because neither of the setups in lanes 1-2 or 5-6 detected properly. Truck speeds were more accurate at 32 km/h (20 mph) than 28 km/h (45 mph) but both were significantly different from radar speeds. The single detection of four vehicles at 32 km/h (20 mph) by Autoscope™ may have affected its speed calculation. The night wet pavement Autoscope™ speed was slightly less accurate than the daytime dry pavement Autoscope™ speed.

6.2.3 Cost Comparisons Between Inductive Loop Detection and Video Detection

Making video detection cost effective requires full utilization of its advantages over inductive loops. This means using its wide area detection features — using one camera to replace several inductive loops and more than two cameras per video processor. This is a likely scenario at signalized intersections. Cost calculations in Chapter 5 result in very competitive costs for video at intersections, based on assumptions that motorist delay and excess fuel consumption for loop installation and/or maintenance were very low. This is very seldom a realistic assumption.

The installing agency could minimize motorist delay and hence costs by carefully selecting the timing of disruptive activities.

6.2.4 Implementation Recommendations

The variables of interest to designers for mounting a CCD camera are: camera focal length, imager size, camera height, offset, horizontal angle, vertical angle, and application category. Two application categories must be considered: freeways and signalized intersections. For this research, the imager size remained constant at 12.7 mm (½ in.) The camera focal length remained constant at 6 mm for field tests replicating one direction of a six-lane freeway. However, it varied from 6 mm to 12 mm in simulations using Microstation for signalized intersections. Field tests used camera heights of 9.1 m (30 ft.), 12.2 m (40 ft.), and 15.1 m (49 ft. - 6 in.), and offsets of 5.34 m (17.5 ft.) and 9.15 m (30.0 ft.). Based on video image processing system manufacturer recommendations, vertical angles for cameras on freeways should be kept near 30 degrees (measured downward from the horizontal plane) to minimize occlusion, although this relatively steep angle limits the horizontal coverage area, especially for some longer camera focal lengths. To the contrary, the vertical angles calculated below for intersections depend more on getting the best coverage rather than adhering to the 30 degree minimum. Horizontal angles were calculated by centering the camera on the viewing area of interest. For freeways, it is the center of the lanes in a particular direction; for intersections, it is the approach being monitored.

6.2.4.1 Freeways

The following criteria apply to freeways; however, site specific needs must also be considered to achieve optimum performance from video image processing systems.

1. Increasing camera height from 9.1 m (30 ft.) to 12.2 m (40 ft.) reduces occlusion; however, sway and vibration may become problematic above 12.2 m (40 ft.) with some supports. Utilizing existing supports will typically limit the camera height to 9.1 to 10.6 m (30 to 35 ft.)

2. A finding of the controlled field testing was that accurate vehicle counts generally occurred farther upstream of the camera location in lanes farther from the camera (e.g., lanes 5 and 6) than in lanes nearest the camera (e.g., lane 1). These results must be interpreted carefully, however, considering that on a high volume freeway, count accuracy is likely to decrease significantly in lanes 5 and 6 due to occlusion by vehicles in the near lanes.

3. Based on interviews with both practitioners and researchers, a general practical limit to the number of adjacent freeway lanes that can be "accurately" counted with one camera mounted not more than 4.6 m (15 ft.) off the roadway is four. Count accuracy in heavy flows will be reduced in lanes farther from the camera.

4. Speed accuracy is important for freeway applications. Studies of Autoscope™ 2004 speed accuracy indicate that unadjusted mean speeds were consistently 15 to 20 percent higher than radar gun mean speeds (mean values from 10 runs by lane, camera height, and vehicle speed category). Adjustment factors derived in this research, one for each of the three camera heights, reduced differences between mean radar gun speed and mean Autoscope™ speeds to approximately plus-or-minus 10 percent.

5. The horizontal angle of the camera (as measured with the direction of traffic) depends upon its focal length, imager size, and the number of lanes in the detection zone. However, an appropriate beginning point for aiming the camera based on the 4.6 m (15 ft.) offset noted above is 30 degrees. For a 12.2 m (40 ft.) camera mounting height, this should aim the camera at a point approximately 24.4 m (80 ft.) away from the base of its support and centered on the four lanes.

6. Based on manufacturer recommendations, the camera's vertical angle with the horizontal plane should be approximately 30 degrees.

6.2.4.2 Signalized Intersections

The following set of assumptions provide the basis of camera settings provided in Table 6-1 for signalized intersections. Obviously, not all intersections fit the assumptions, but these are intended as guides to assist the installer/designer in getting started. Refinement of camera orientation based on site specific features is required. These criteria were developed, not by field testing, but by the computer software, Microstation. As this technique is refined, it may reduce the need for costly field data acquisition. The camera height is either 9.1 m (30 ft.) or 12.2 m (40 ft.), its offset from the outside travel lane is 1.54 m (5.0 ft.), and lane widths are 3.4 m (11 ft.) All imagers are 12.7 mm (½ in.) and camera focal lengths are 6 mm, 8 mm, 10 mm, and 12 mm.

6.3 FUTURE RESEARCH

The results of this study provide guidance on the use and placement of video image processing systems on freeways. The study design required that some variables remain constant during the majority of the data collection phase. These included: lighting, weather, vehicle speed, vehicle color, and vehicle size. Actual freeway traffic flow is much more dynamic, necessitating further research for a more comprehensive understanding of other variables.

Further testing is recommended to verify the passenger car speed percent differences between speeds determined by the Autoscope™ system and speeds obtained by radar. Further testing is also recommended to determine if the same percent difference values can be applied for a mixed vehicle type condition. Further research is also needed to study how gap distance affects the system's ability to accurately detect vehicles and the system's ability to accurately determine vehicle speeds.

Table 6-1. Camera Orientation at Intersections Mounted at 9.1 m (30 ft) and 12.2 (40 ft) Heights

Intersection	Camera (mm)	Horizontal FOV Angle	9.1 m (30 ft) Ht.		12.2 m (40 ft) Ht.	
			Horizontal Angle (right of vertical)	Vertical Angle (below horiz.)	Horizontal Angle (right of vertical)	Vertical Angle (below horiz.)
4x4	6	56.1	15.5	17.8	25.5	22.1
	8	43.6	21.3	17.3	21.8	26.3
	10	35.5	18.6	19.6	18.9	28.4
	12	30	24.7	24.7	16.9	30.1
6x6	6	56.1	27.8	4.0	27.7	10.0
	8	43.6	20.9	5.8	20.8	13.6
	10	35.5	18.7	20.3	15.9	15.4
	12	30	17.1	12.7	14.4	17.2
8x8	6	56.1	25.2	3.0	26.6	4.3
	8	43.6	20.4	3.1	20.5	8.2
	10	35.5	19.3	13.3	17.2	10.3
	12	30	15.9	16.9	14.0	12.2

Several video image processing systems are available for use in both intersection and freeway applications. These systems must be evaluated in a standardized manner to compare the capabilities and limits of each system. Standardized methods and procedures to effectively evaluate existing and future video image processing systems are needed. A database showing the development status and capabilities of each system would aid transportation agencies immensely in choosing the appropriate video image processing system for a particular application.

Finally, TxDOT needs a set of specifications for testing future detectors of all types. This will include both field test guidelines and bench test guidelines. Field testing would be used to qualify a specific system, whereas bench testing would be used more for acceptance testing of approved systems. It is anticipated that Project 0-1715 will address the types of testing and develop more specific tests to meet TxDOT's needs.

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8.0 APPENDIX A

DETECTION GRAPHICS

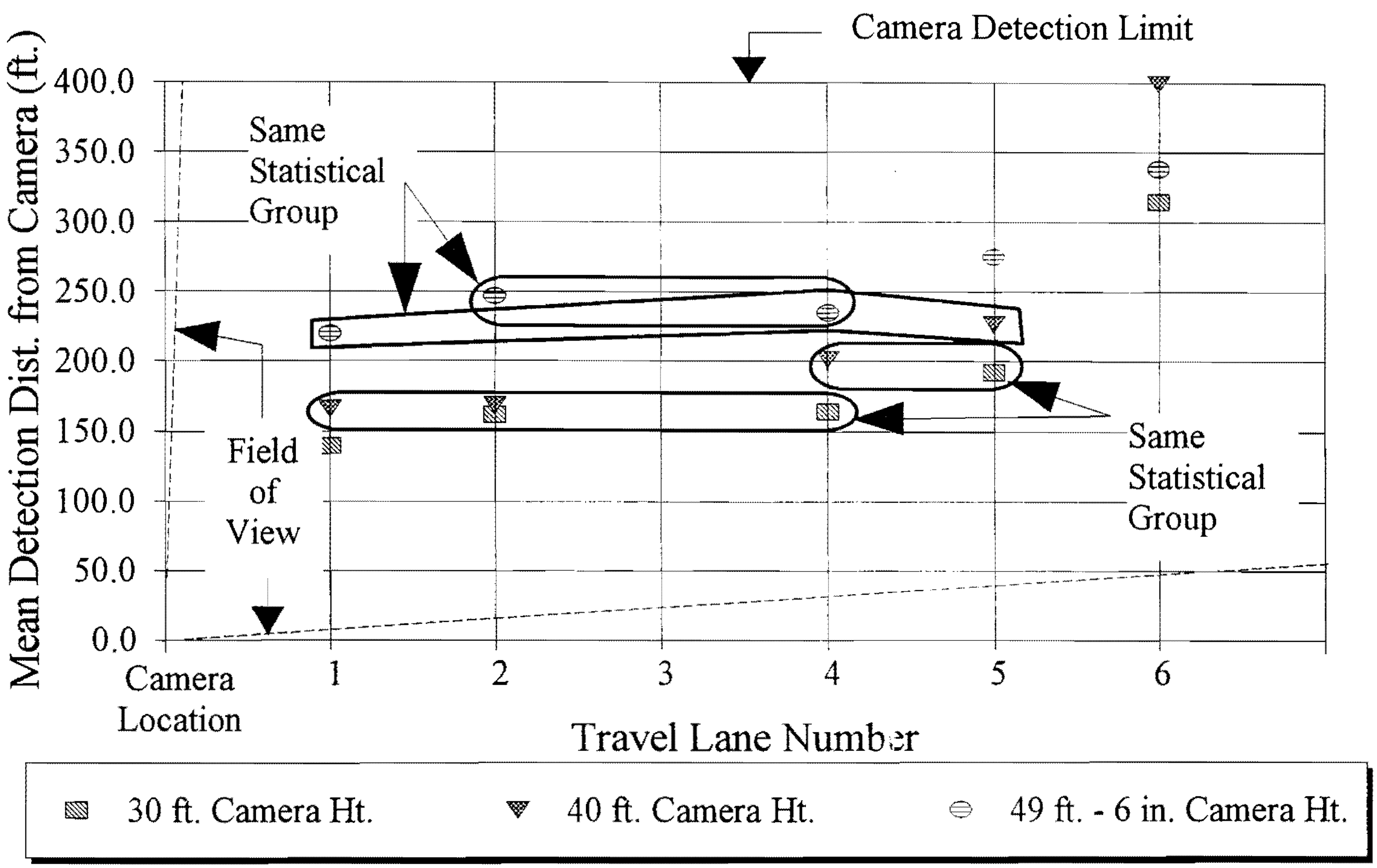

Figure A-1. Video Image System's Mean Detection Distance -- 20 mph (Passenger Cars)

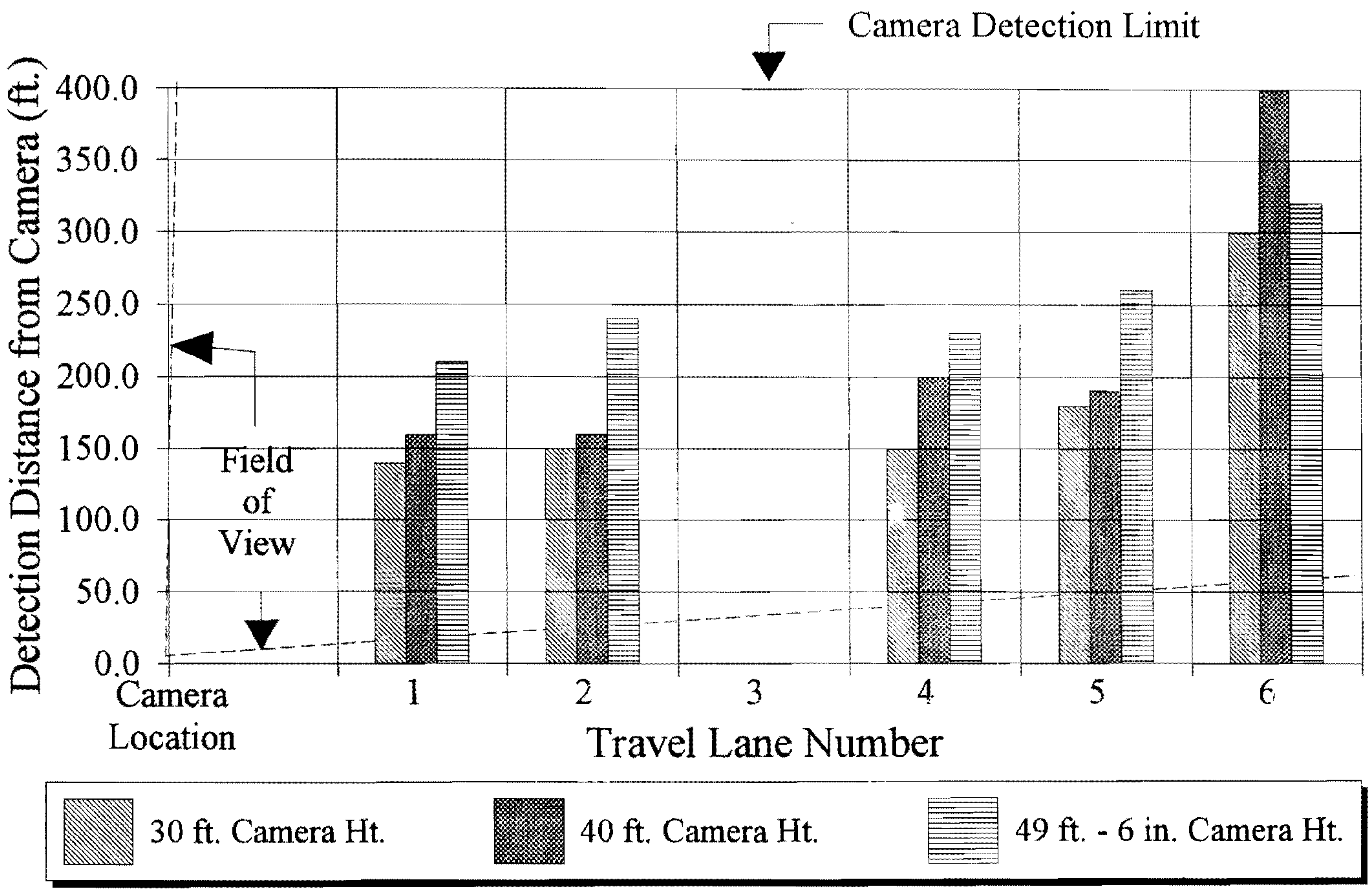

Figure A-2. Video Image System's Detection Range--32 km/h (20 mph) (Passenger Cars)

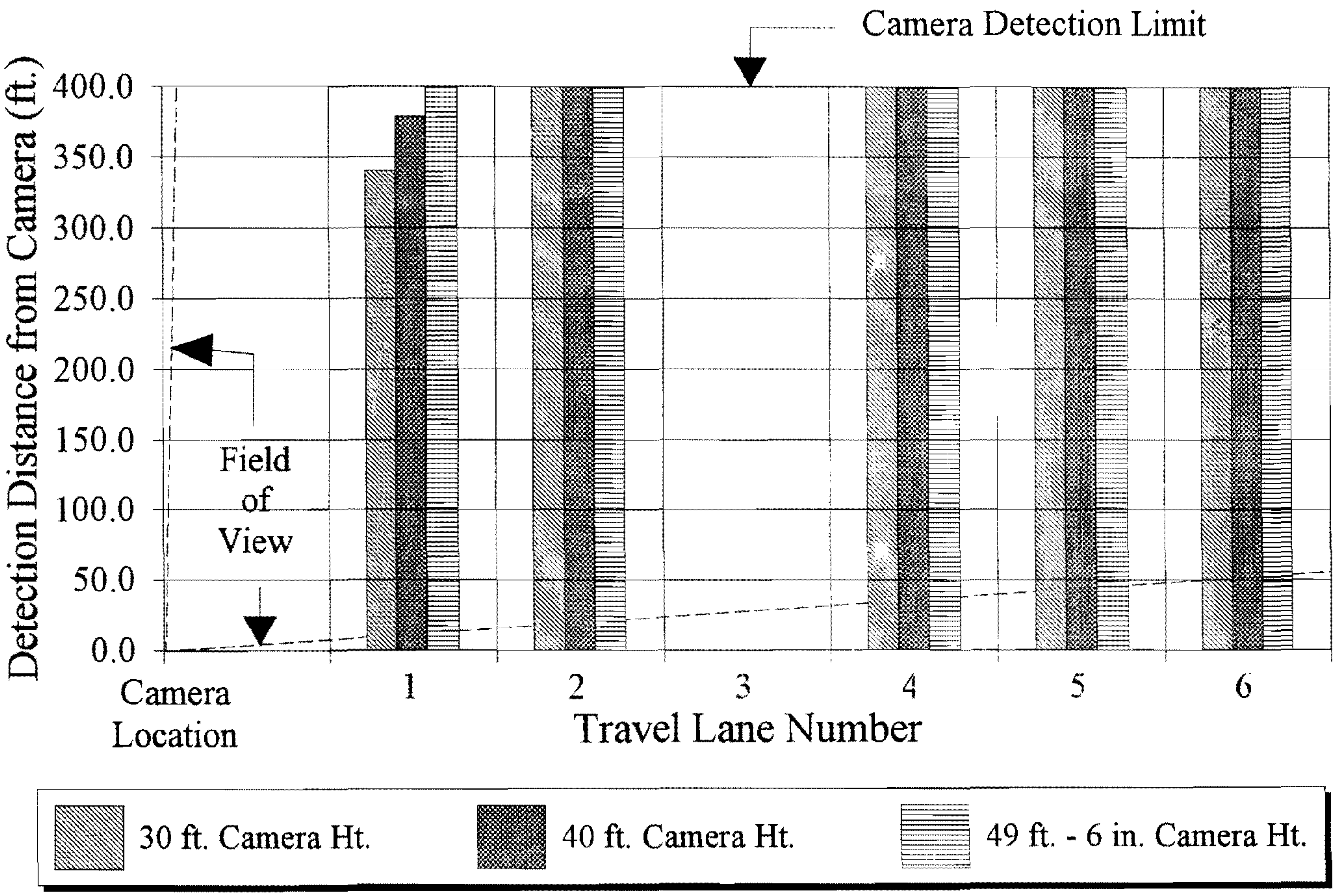

Figure A-3. Video Image System's Detection Range -- 72 km/h (45 mph) (Passenger Cars)

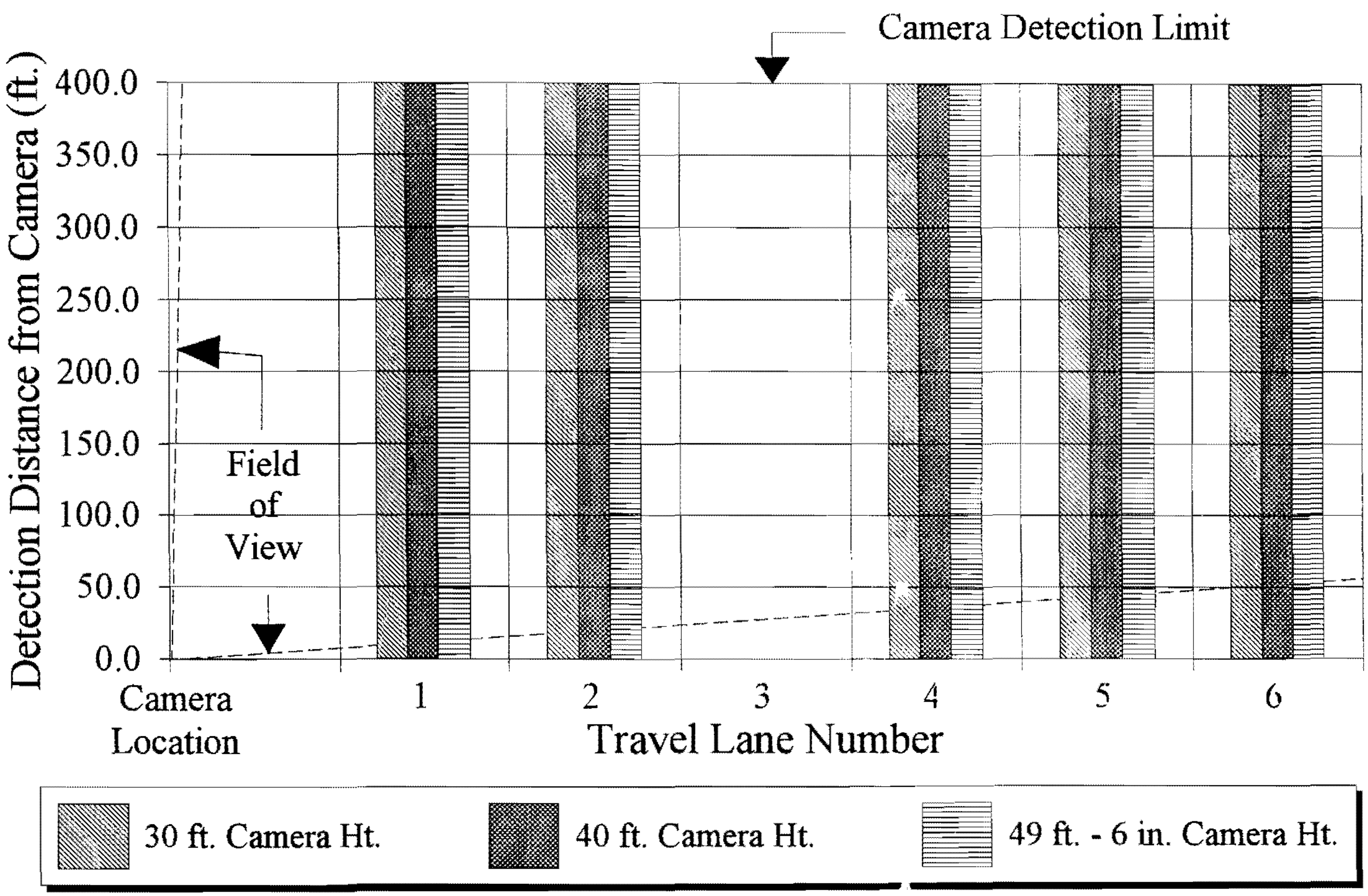

Figure A-4. Video Image System's Detection Range -- 88 km/h (55 mph) (Passenger Cars)

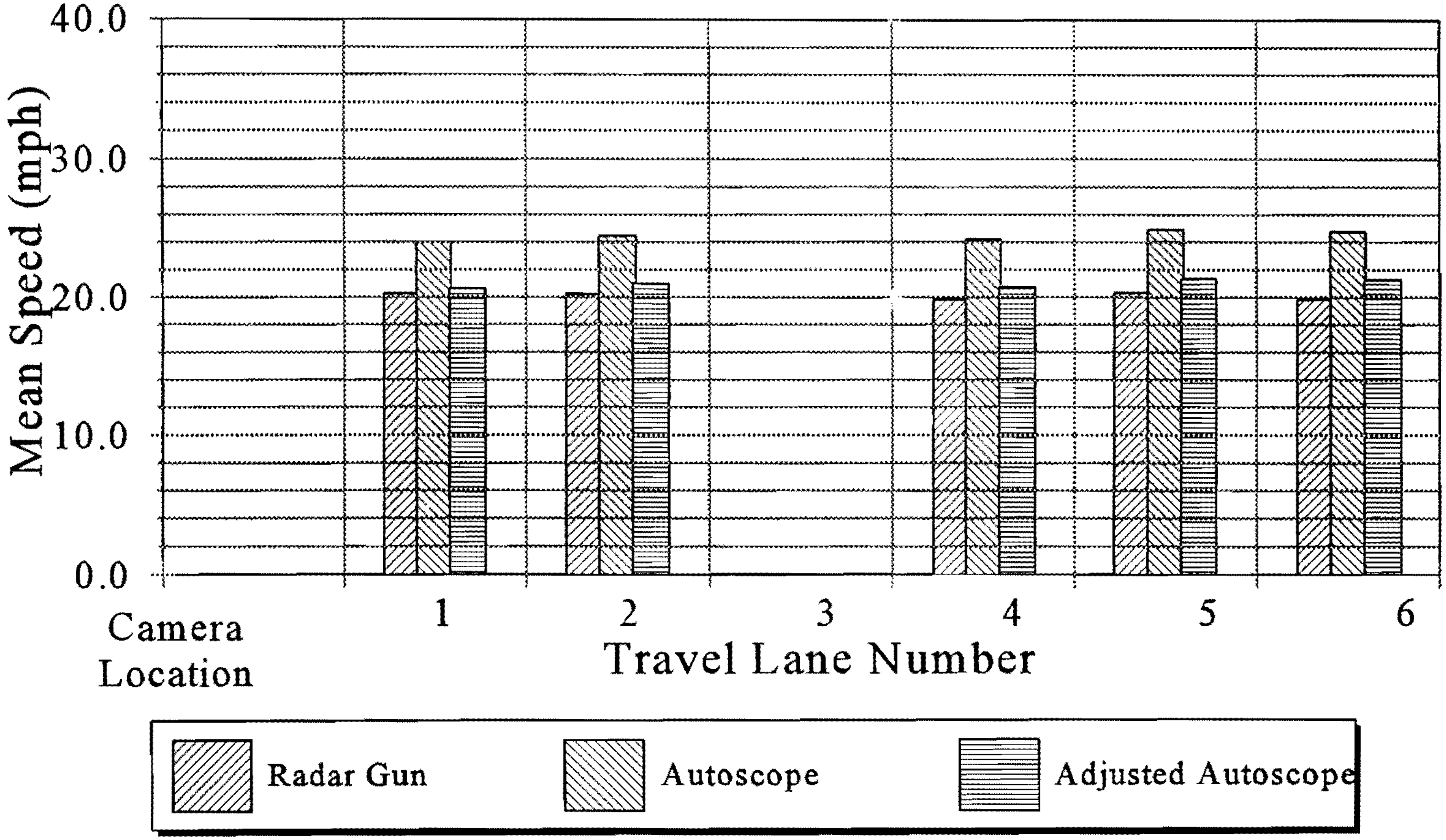

Figure A-5. Passenger Car Speed Comparison
(9.1 m (30 ft.) Camera Height -- 32 km/h (20 mph))

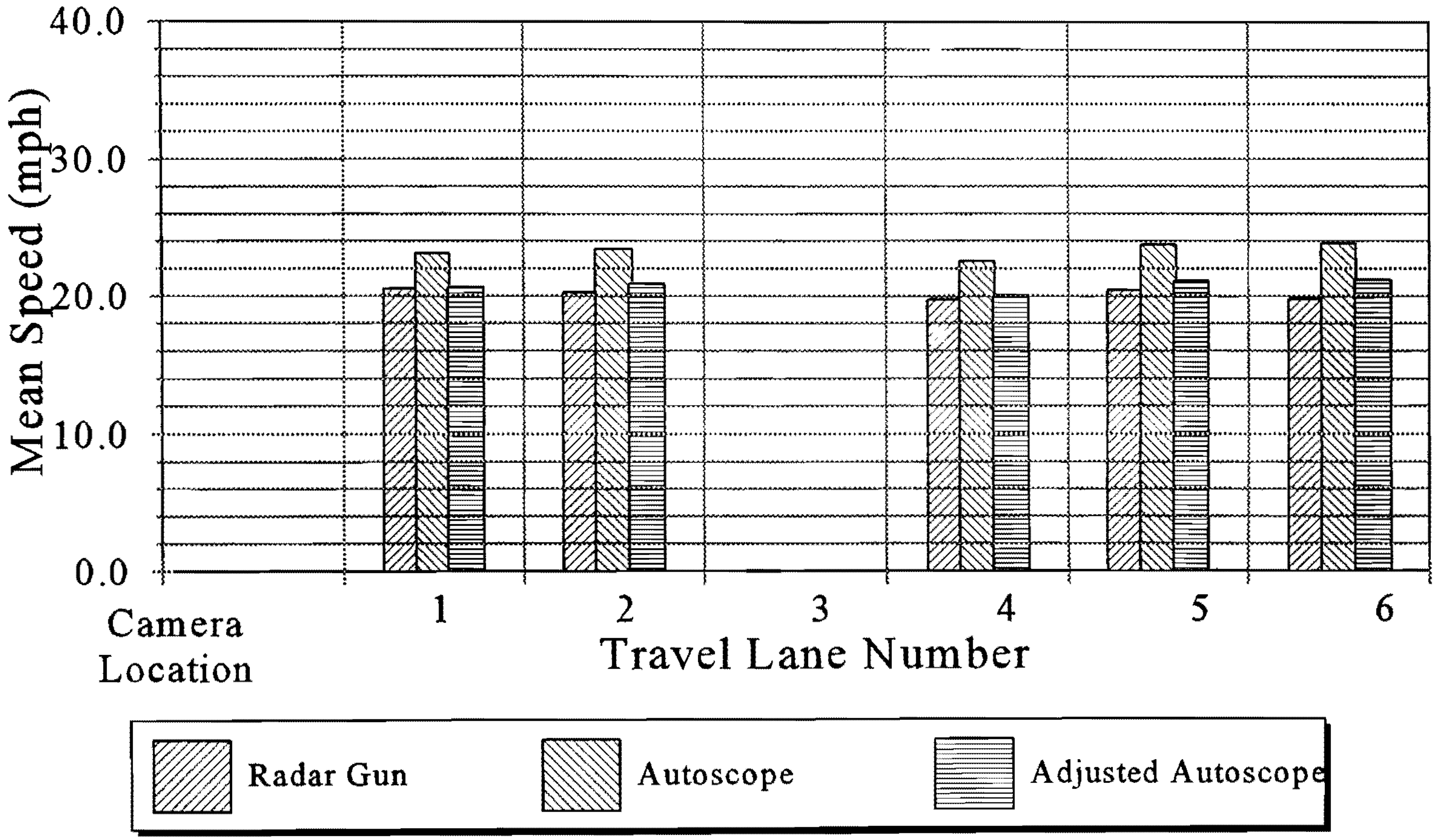

Figure A-6. Passenger Car Speed Comparison
(12.2 m (40 ft.) Camera Height -- 32km/h (20 mph))

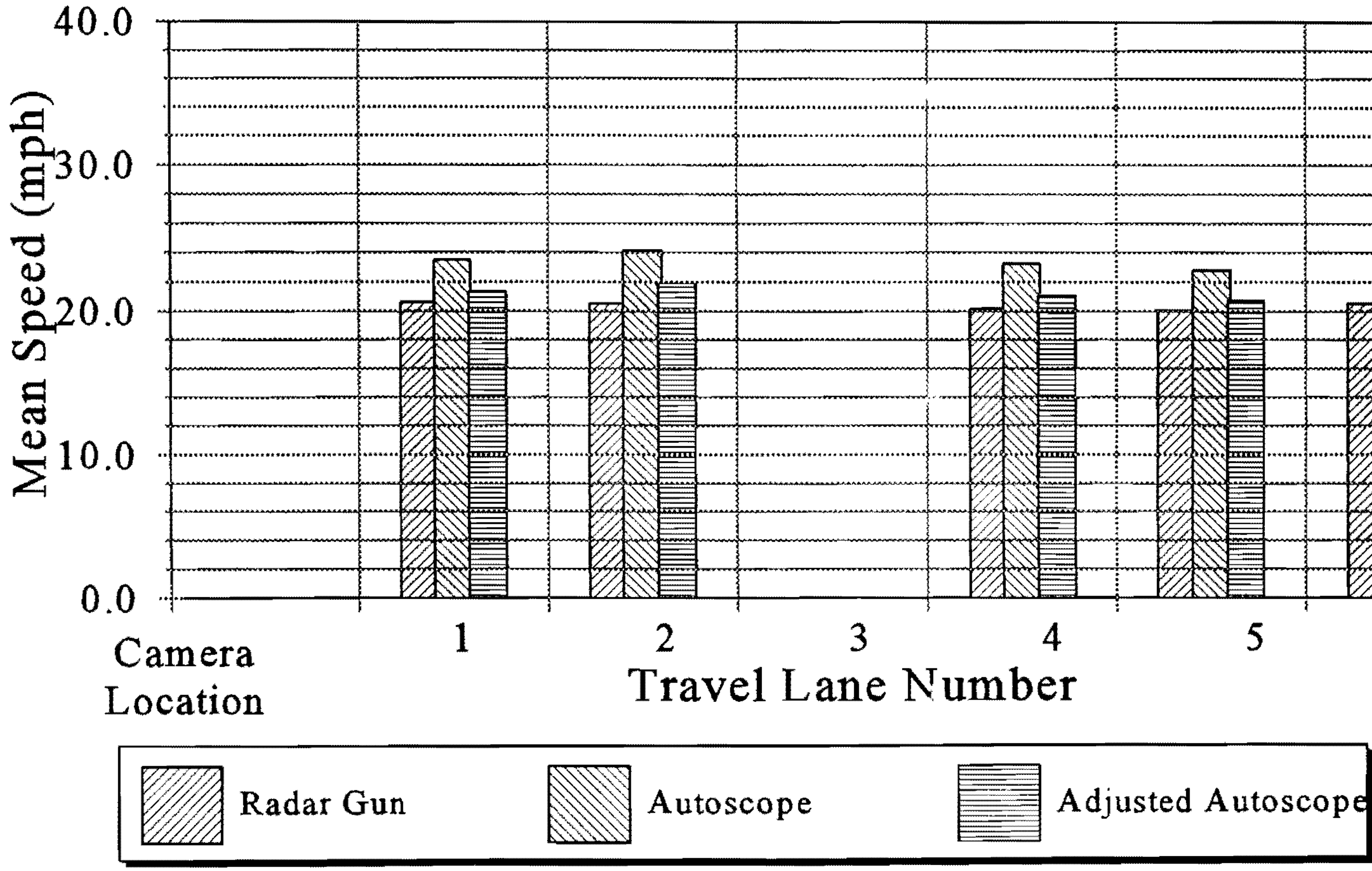

Figure A-7. Passenger Car Speed Comparison
(15.1 m (49 ft. - 6 in.) Camera Height -- 32 km/h (20 mph))

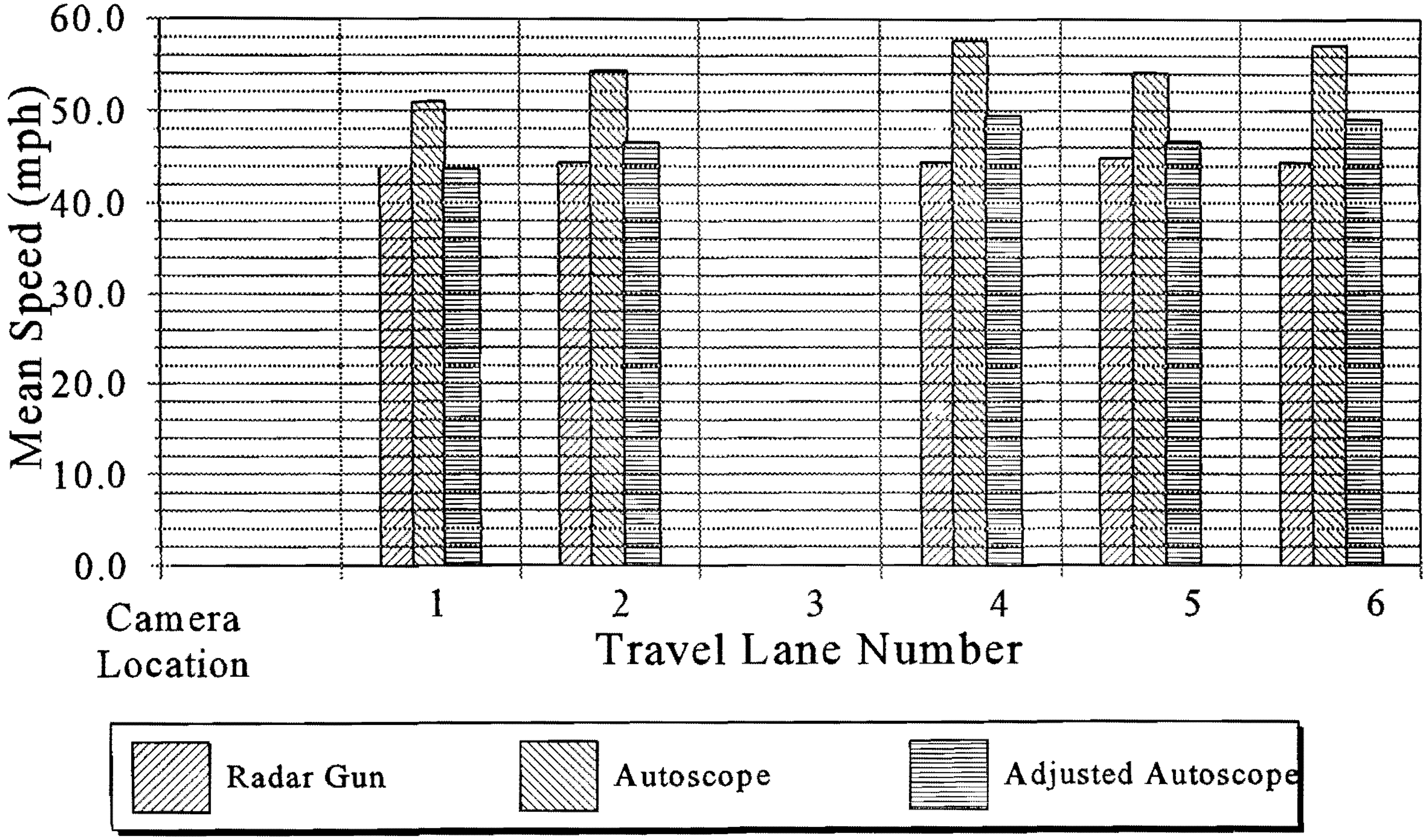

Figure A-8. Passenger Car Speed Comparison
(9.1 m (30 ft.) Camera Height -- 72 km/h (45 mph))

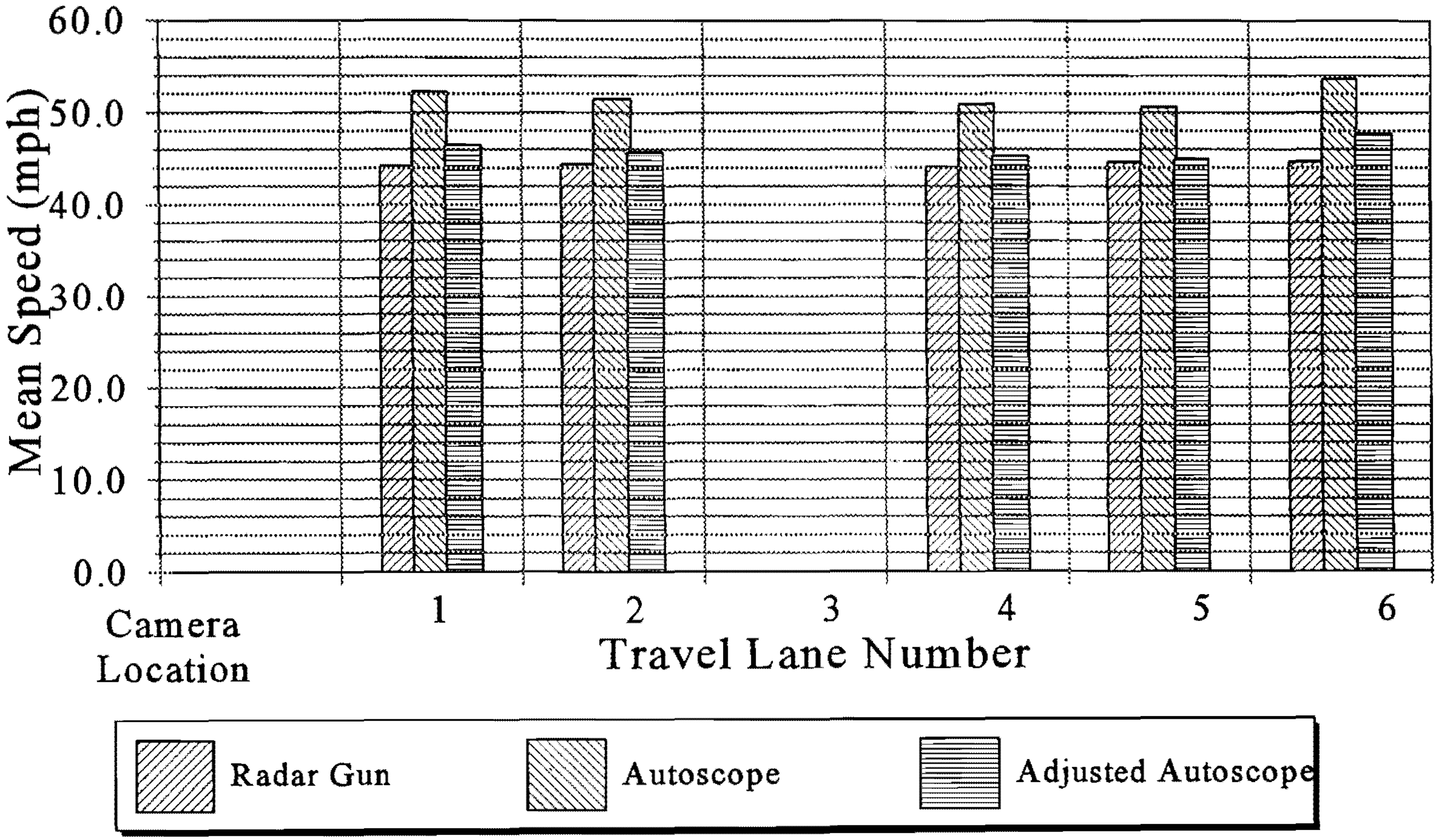

Figure A-9. Passenger Car Speed Comparison
(12.2 m (40 ft.) Camera Height -- 72 km/h (45 mph))

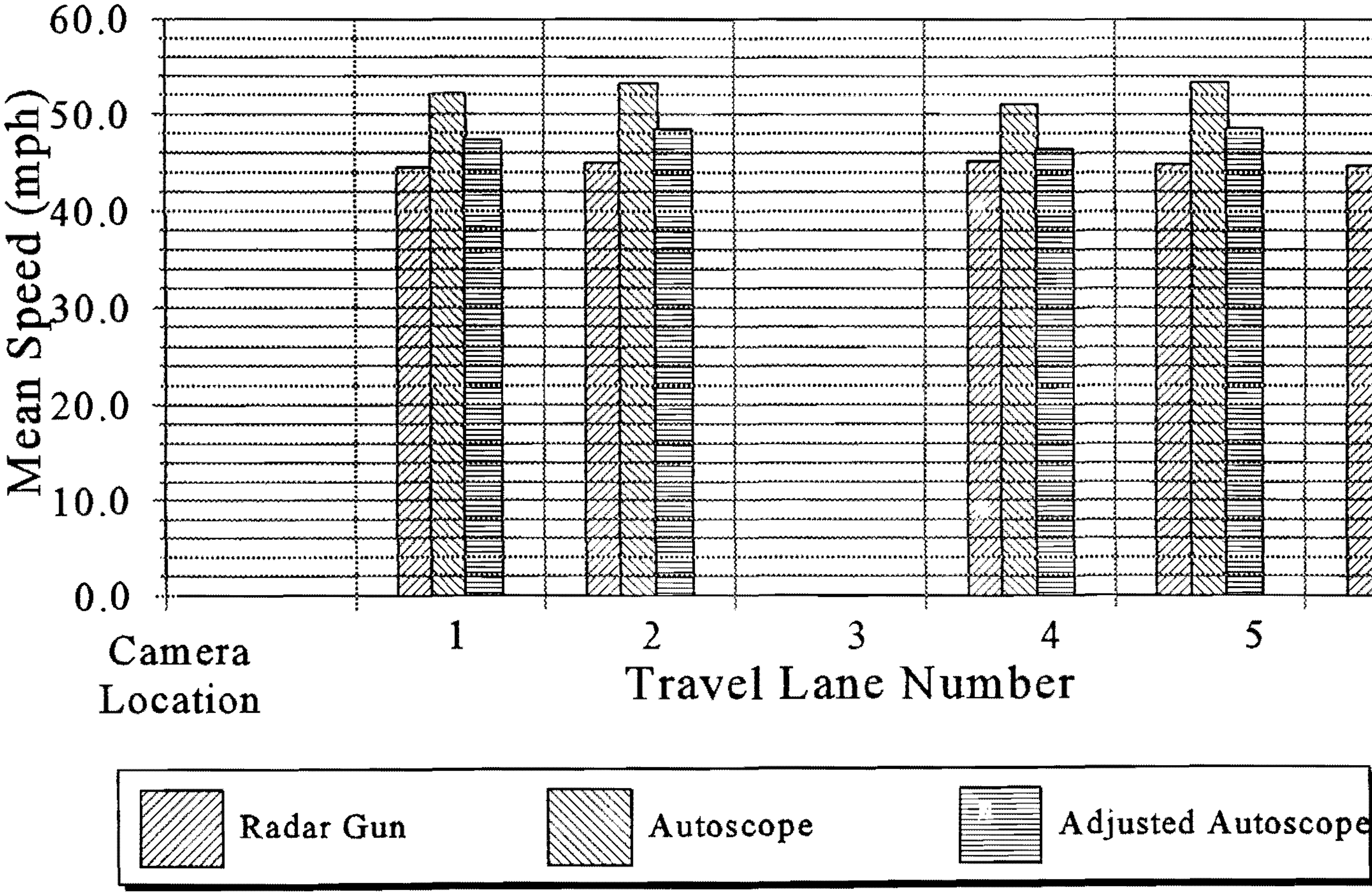

Figure A-10. Passenger Car Speed Comparison
(15.1 m (49 ft. - 6 in.) Camera Height -- 72 km/h (45 mph))

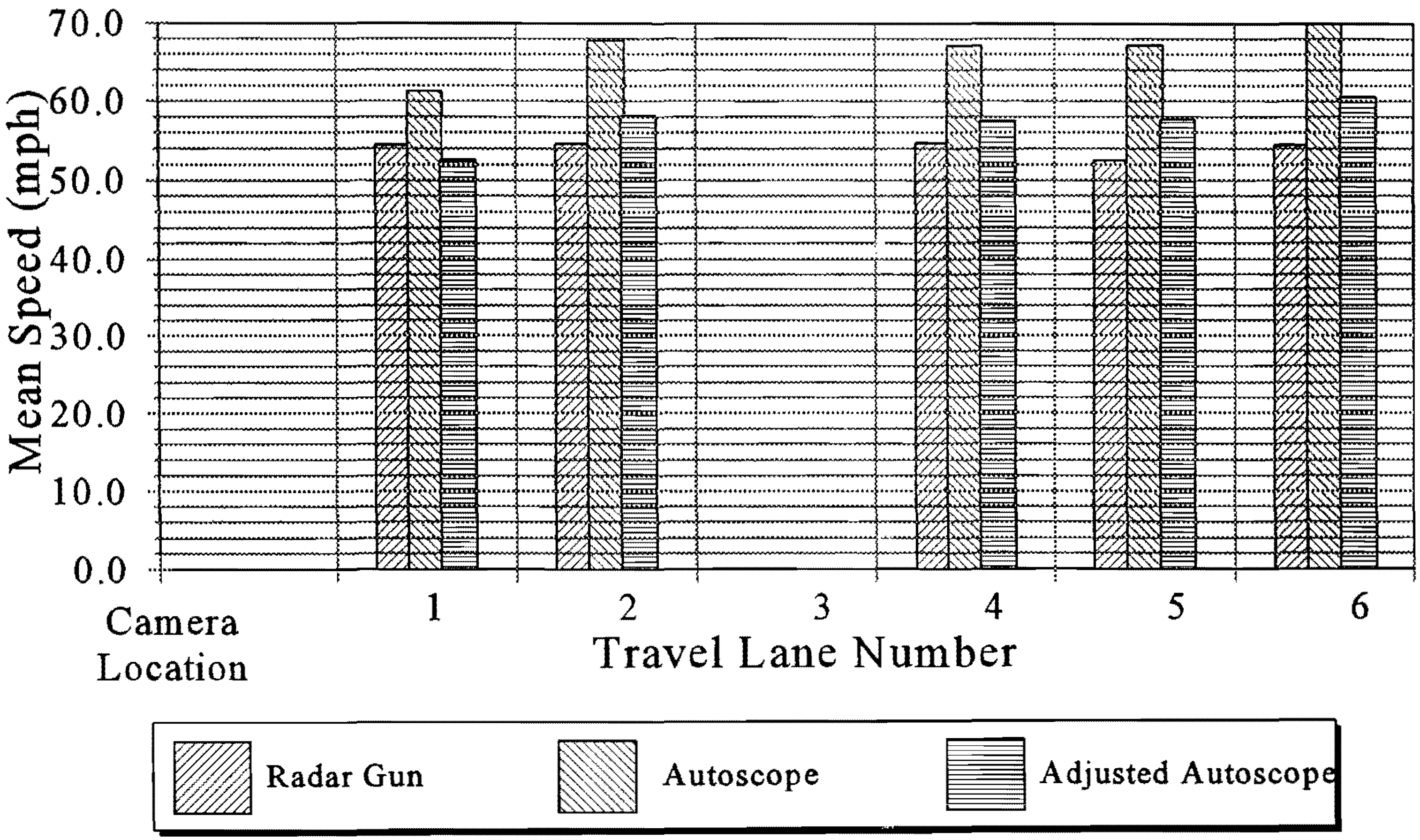

Figure A-11. Passenger Car Speed Comparison
(9.1 m (30 ft.) Camera Height -- 88 km/h (55 mph))

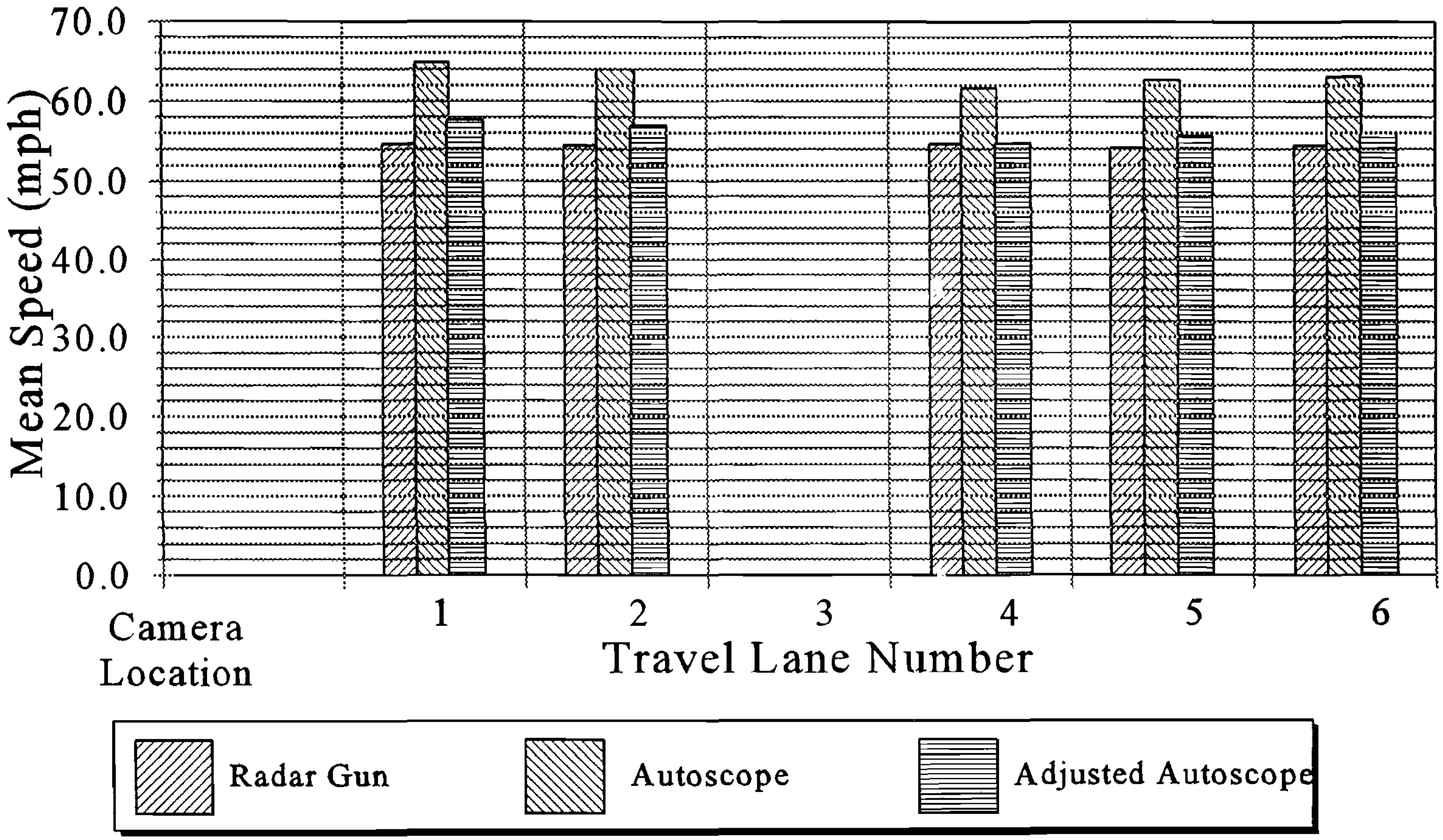

Figure A-12. Passenger Car Speed Comparison
(12.2 m (40 ft.) Camera Height -- 88 km/h (55mph))

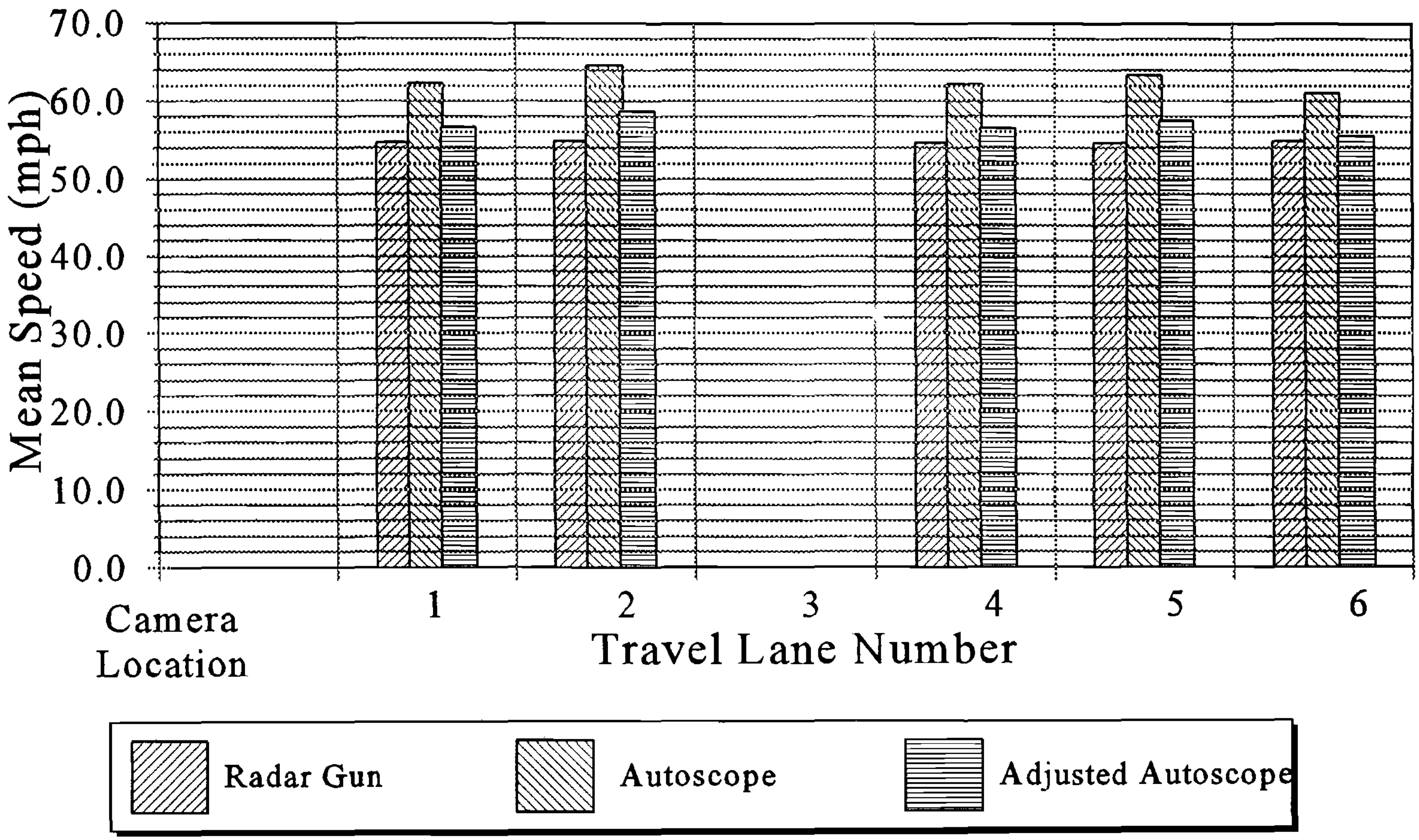

Figure A-13. Passenger Car Speed Comparison
(15.1 m (49 ft. - 6 in.) Camera Height -- 88 km/h (55 mph))

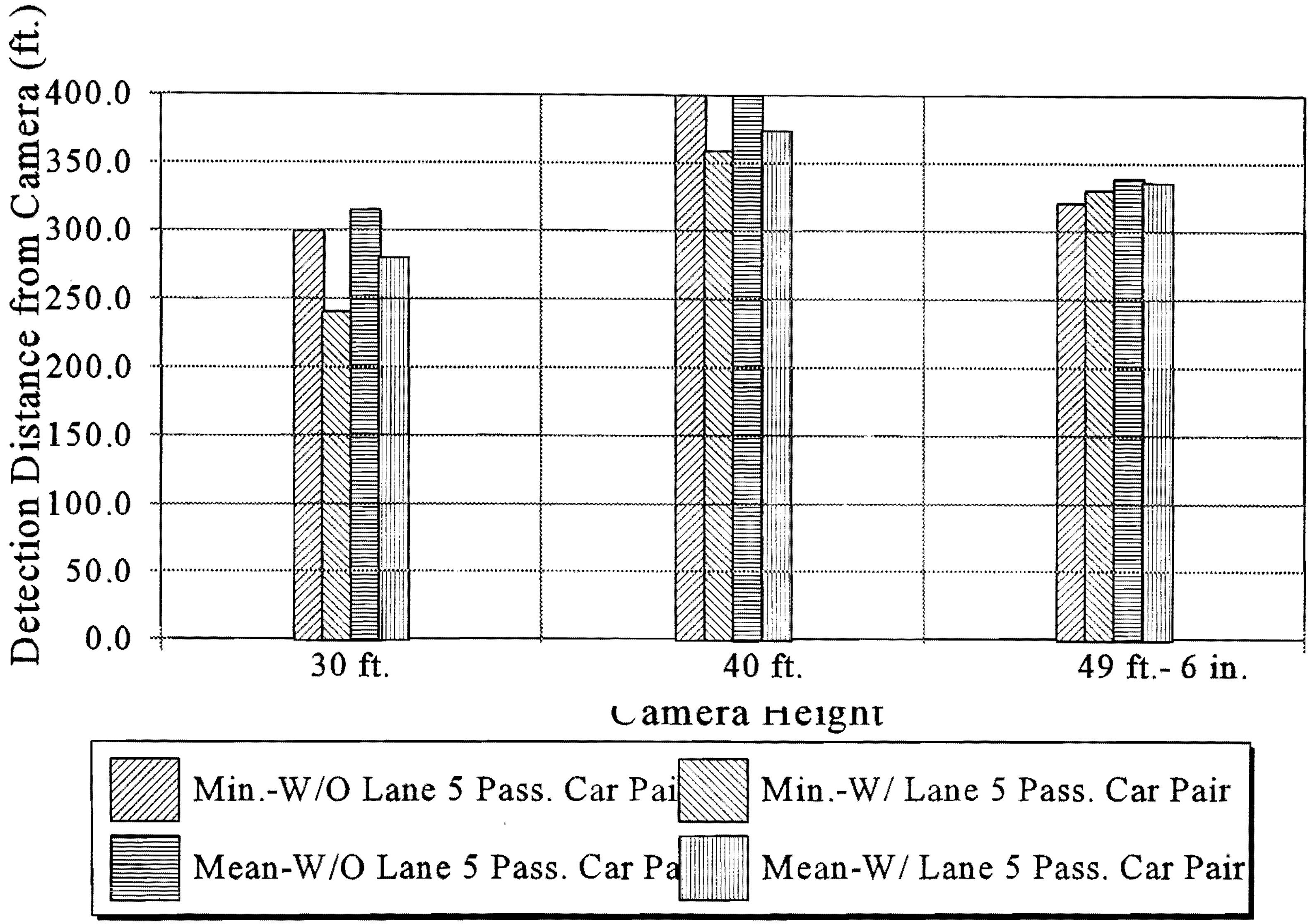

Figure A-14. Lane 6 Detection Comparison -- 32 km/h (20 mph) (Passenger Cars)

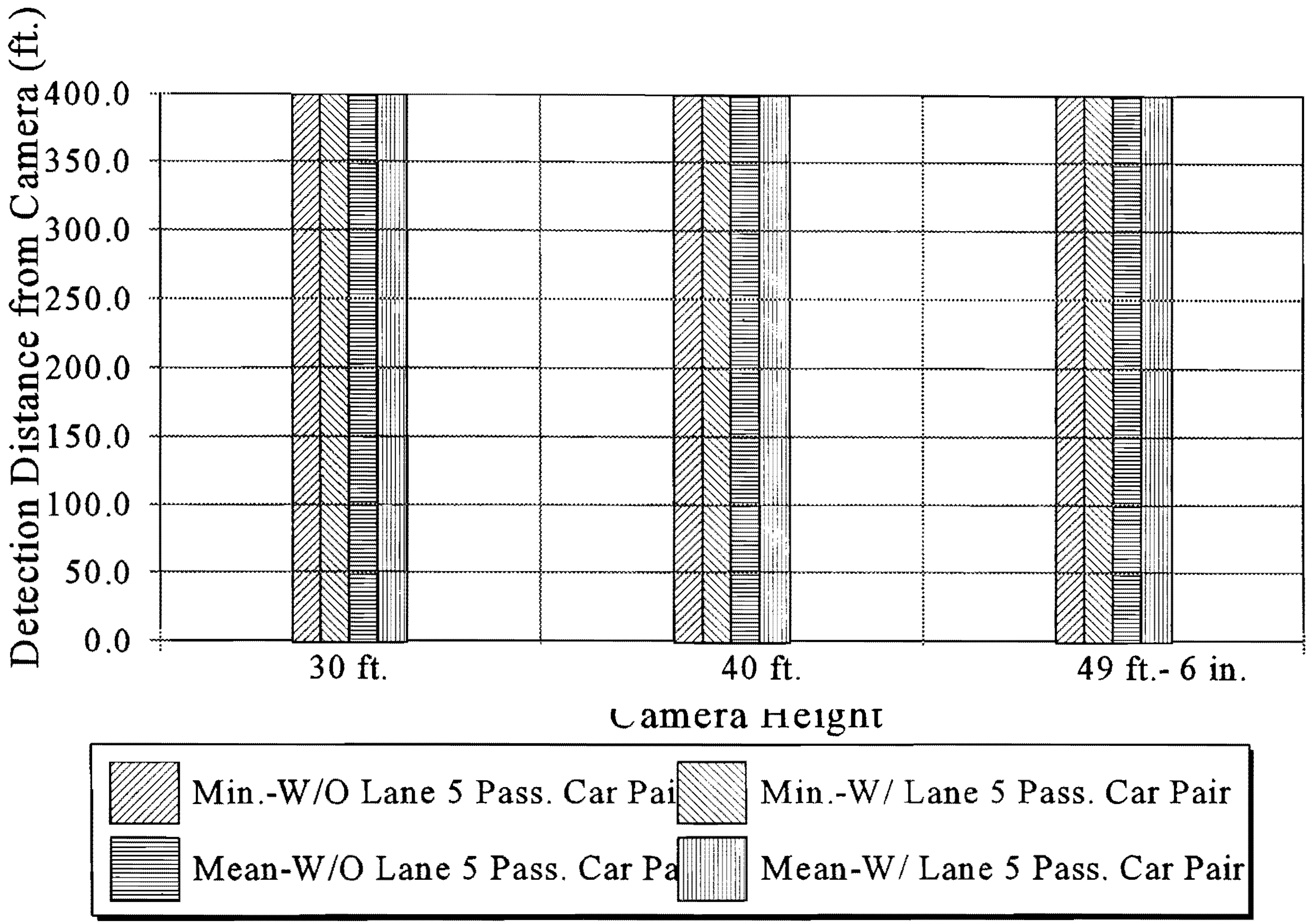

Figure A-15. Lane 6 Detection Comparison -- 72 km/h (45 mph) (Passenger Cars)

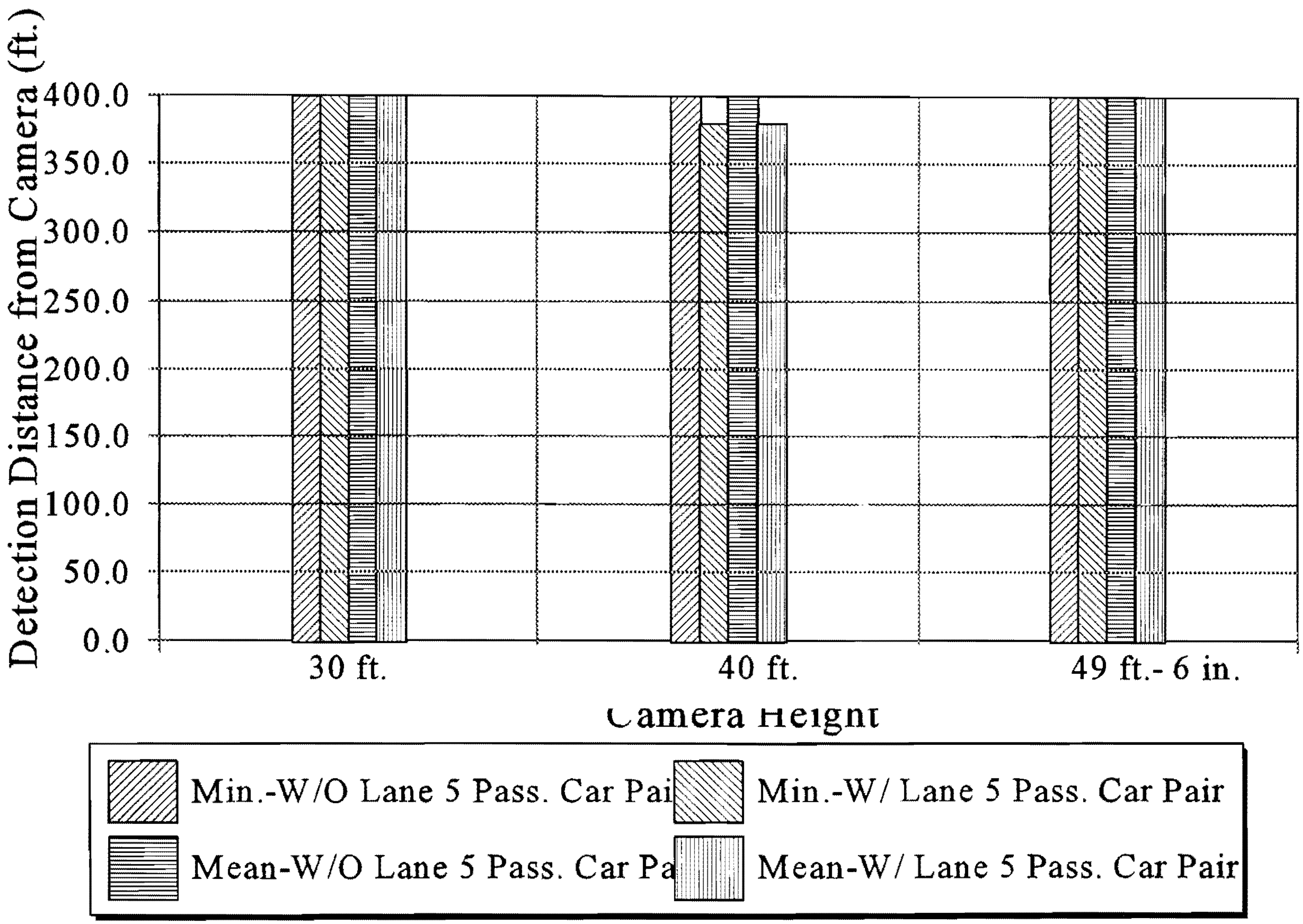

Figure A-16. Lane 6 Detection Comparison -- 88 km/h (55 mph) (Passenger Cars)

9.0 APPENDIX B

AUTOSCOPE TESTING DATA

AUTOSCOPE TESTING DATA

Camera Height: 19.1 meters (30 feet) Vehicle Speed: 32 km/h (20 mph)

Lane Offset from Camera: 17.5 feet
(Lane No. 1)

Run Num.	Detector Location	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1	139.9	19	23.0	19.7
2	139.9	21	24.5	21.0
3	139.9	20	23.5	20.1
4	139.9	20	24.0	20.6
5	130.0*	21	24.0	20.6
6	139.9	20	24.0	20.6
7	139.9	20	24.5	21.0
8	139.9	20	24.0	20.6
9	139.9	21	24.0	20.6
10	139.9	21	25.0	21.4
11	139.9	20	24.5	21.0
12		20	23.0	19.7

*Video shifted
**Adjusted Autoscope speed

Lane Offset from Camera: 30.0 feet
(Lane No. 2)

Run Num.	Detector Location	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1		21		0.0
2	160.0	20	24.5	21.0
3	150.1	20	24.0	20.6
4	160.0	20	24.5	21.0
5	150.1	20	25.0	21.4
6	170.0	20	25.0	21.4
7	170.0	21	25.0	21.4
8	140.1*	20	25.0	21.4
9	170.0	20	24.0	20.6
10	160.0	20	24.0	20.6
11	170.0	21	24.0	20.6
12	160.0	20	24.0	20.6

*Video shifted

Lane Offset from Camera: 55.0 feet
(Lane No. 4)

Run Num.	Detector Location	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.
1	160.0	19		
2	160.0	19	24.0	20.6
3	160.0	20	24.0	20.6
4	160.0	20	24.5	21.0
5	150.0	20	25.0	21.4
6	170.1	20	25.0	21.4
7	150.0	20	24.0	20.6
8	170.1	20	24.0	20.6
9	140.1*	20	24.0	20.6
10	170.1	19	24.0	20.6
11	179.8	20	24.0	20.6
12	179.8	20	24.0	20.6

*Video shifted
**Adjusted Autoscope speed

Lane Offset from Camera: 67.5 feet
(Lane No. 5)

Run Num.	Detector Location	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.
1	200.4	20		
2	179.8	20	24.0	20.6
3	200.4	20	25.0	21.4
4	179.8	20	25.0	21.4
5	179.8	20	25.0	21.4
6	179.8	21	25.0	21.4
7	200.4	20	25.0	21.4
8	200.4	20	25.0	21.4
9	200.4	20	25.0	21.4
10	200.4	20	25.0	21.4
11	189.8	21	25.0	21.4
12	200.4	21	25.0	21.4

AUTOSCOPE TESTING DATA

Camera Height: 19.1 meters (30 feet) Vehicle Speed: 32 km/h (20 mph)

Lane Offset from Camera: 80.0 feet
(Lane No. 6 - without Occlusion)

Run Num.	Detector Location	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.
1	299.6	20		
2	319.9	20	25.5	21.9
3	319.9	19	25.5	21.9
4	299.6	20	24.0	20.6
5	319.9	20	24.0	20.6
6	319.9	21	25.0	21.4
7	299.6	20	24.5	21.0
8	319.9	20	24.0	20.6
9	319.9	20	25.0	21.4
10	319.9	19	25.0	21.4
11	319.9	19	25.0	21.4
12	319.9	20	25.0	21.4

**Adjusted Autoscope speed

Lane Offset from Camera: 80.0 feet
(Lane No. 6 - with Occlusion)

Run Num.	Detector Location	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.
1	299.6	20	24.0	20.6
2	240.2	20	27.0	23.1
3	299.6	20		0.0
4	319.9	20	25.5	21.9
5	240.2	19	25.5	21.9
6	240.2	20	25.0	21.4
7	240.2	20	24.5	21.0
8	299.6	19	24.0	20.6
9	299.6	20	24.0	20.6
10	280.6	20	25.5	21.9
11	299.6	21	26.5	22.7
12	299.6	21	27.0	23.1

AUTOSCOPE TESTING DATA

Camera Height: 19.1 meters (30 feet) Vehicle Speed: 72 km/h (45 mph)

Lane Offset from Camera: 17.5 feet
(Lane No. 1)

Run Num.	Detector Location	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1		44	50.5	43.29
2	340.2	44	50.0	42.86
3	340.2	43	50.0	42.86
4	340.2	44	51.0	43.71
5	340.2	44	51.0	43.71
6	340.2	45	51.0	43.71
7	340.2	43	50.5	43:29
8	340.2	45	51.0	43.71
9	319.8*	43		
10	340.2	43	52.0	44.57
11	340.2	44	52.0	44.57
12	340.2	45	51.0	43.71

*Video shifted

**Adjusted Autoscope Speed

Lane Offset from Camera: 30.0 feet
(Lane No. 2)

Run Num.	Detector Location	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	400.9	44	55.0	47.14
2	400.9	44	56.0	48.00
3	400.9	44	55.0	47.14
4	380.0*	44	54.5	46.71
5	400.9	44	53.5	45.86
6	400.9	45	54.0	46.29
7	400.9	45	54.5	46.71
8	400.9	44	54.5	46.71
9	400.9	45	54.0	46.29
10	400.9	45	54.0	46.29
11	400.9	43	53.5	45.86
12		45	54.0	46.29

*Video shifted

AUTOSCOPE TESTING DATA

Camera Height: 19.1 meters (30 feet) Vehicle Speed: 72 km/h (45 mph)

Lane Offset from Camera: 55.0 feet (Lane No. 4)

Run Num.	Detector Location	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1		44	56.5	48.43
2	400.3	45	58.5	50.14
3	400.3	45	59.0	50.57
4	400.3	44	59.5	51.00
5	400.3	44	58.0	49.71
6	400.3	44	57.0	48.86
7	400.3	45	56.5	48.43
8	400.3	44	56.5	48.43
9	400.3	44	56.5	48.43
10	400.3	44	58.0	49.71
11	400.3	45	58.0	49.71
12	400.3	45	58.0	49.71

**Adjusted Autoscope Speed

Lane Offset from Camera: 67.5 feet (Lane No. 5)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	399.5			
2	399.5		51.5	44.14
3	399.5	45	53.5	45.86
4	399.5	45	53.5	45.86
5	399.5	46	54.0	46.29
6	399.5	45	54.0	46.29
7	399.5	44	54.0	46.29
8	399.5	45	55.0	47.14
9	399.5	45	55.0	47.14
10	399.5	44	55.0	47.14
11	399.5	45	55.0	47.14
12	399.5	45	55.0	47.14

Lane Offset from Camera: 80.0 feet (Lane 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	399.7	45	57.5	49.29
2	399.7	45	59.5	51.00
3	399.7	45	59.5	51.00
4	399.7	44	58.0	49.71
5	399.7	44	56.0	48.00
6	399.7	45	56.0	48.00
7	399.7	44	56.0	48.00
8	399.7	44	56.5	48.43
9	399.7	45	57.0	48.86
10	399.7	44	57.0	48.86
11	399.7	43	56.5	48.43
12	399.7	44	56.5	48.43

Lane Offset from Camera: 80.0 feet (Lane No. 6 w/ Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	400.2			
2	400.2	44	52.5	45.00
3	400.2	44	53.0	45.43
4	400.2	44	52.0	44.57
5	400.2	45	53.0	45.43
6	400.2	44	53.0	45.43
7	400.2	45	54.0	46.29
8	400.2	45	53.0	45.43
9	400.2	45	54.0	46.29
10	400.2	44	53.0	45.43
11	400.2	45	54.0	46.29
12	400.2	45	54.0	46.29

**Adjusted Autoscope Speed

AUTOSCOPE TESTING DATA

Camera Height: 19.1 meters (30 feet) Vehicle Speed: 88 km/h (55mph)

Lane Offset from Camera: 17.5 feet (Lane No. 1)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1		53	56.0	48.0
2	399.9	54	60.5	51.9
3	399.9	54	61.0	52.3
4	399.9	55	61.5	52.7
5	399.9	53	62.0	53.1
6	399.9	56	61.5	52.7
7	399.9	54	61.0	52.3
8	399.9	54	61.0	52.3
9	399.9	55	64.5	55.3
10	399.9	55	64.5	55.3
11	399.9	55	61.5	52.7
12	399.9	55	61.0	52.3

**Adjusted Autoscope Speed

Lane Offset from Camera: 30.0 feet (Lane No. 2)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	400.9	55	68.0	58.3
2	400.9	55	68.0	58.3
3	400.9	54	68.0	58.3
4	400.9	55	68.0	58.3
5	400.9	54	68.0	58.3
6	400.9	54	68.0	58.3
7	400.9	55	67.5	57.9
8	400.9	55	67.5	57.9
9	400.9	55	67.5	57.9
10	400.9	56	67.5	57.9
11	400.9	54	67.5	57.9
12	400.9	54	68.5	58.7

Lane Offset from Camera: 55.0 feet (Lane No. 4)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	380.3*	55	58.0	49.7
2	400.3	54	63.0	54.0
3	400.3	55	68.5	58.7
4	400.3	55	66.0	56.6
5	400.3	55	66.0	56.6
6	400.3	55	71.0	60.9
7	400.3	55	71.0	60.9
8	400.3	55	66.0	56.6
9	400.3	54	71.0	60.9
10	400.3	55	69.5	59.6
11	400.3	55	68.0	58.3
12	400.3	54	68.0	58.3

*Not all detectors set
**Adjusted Autoscope Speed

Lane Offset from Camera: 67.5 feet (Lane No. 5)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	399.5		68.5	58.7
2	399.5		68.0	58.3
3	399.5		67.0	57.4
4	399.5	55		
5	399.5	46	67.0	57.4
6	399.5	55	67.0	57.4
7	399.5	55	67.0	57.4
8	399.5	54	68.0	58.3
9	399.5		67.5	57.9
10	399.5		67.0	57.4
11	399.5			
12	399.5		67.0	57.4

AUTOSCOPE TESTING DATA

Camera Height: 19.1 meters (30 feet) Vehicle Speed: 88 km/h (55 mph)

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1	379.3*	54	70.5	60.4
2	399.7	54	71.0	60.9
3	399.7	55	70.0	60.0
4	399.7	54	71.0	60.9
5	399.7	55	71.0	60.9
6	399.7	55	71.0	60.9
7	399.7	54	71.0	60.9
8	399.7	55	71.0	60.9
9	399.7	54	71.0	60.9
10	399.7	55	70.5	60.4
11	399.7	54	70.0	60.0
12	399.7	54	70.0	60.0

*Not all detectors set
**Adjusted Autoscope Speed

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/ Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1	400.2		70.5	60.4
2	400.2		71.0	60.9
3	400.2		70.0	60.0
4	400.2	55	70.0	60.0
5	400.2		70.0	60.0
6	400.2		70.0	60.0
7	400.2	55	70.0	60.0
8	400.2		70.0	60.0
9	400.2		70.0	60.0
10	400.2		68.0	58.3
11	400.2		68.0	58.3
12	299.6***	55	70.0	60.0

***Videotape stopped early causing disruption in detectors

AUTOSCOPE TESTING DATA

Camera Height: 12.2 meters (40 feet) Vehicle Speed: 32 km/h (20 mph)

Lane Offset from Camera: 17.5 feet
(Lane No. 1)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1		20		
2	149.6*	21	24.5	21.8
3	159.6	20	23.0	20.4
4	159.6	20	23.0	20.4
5	159.6	21	23.0	20.4
6	179.9	20	23.0	20.4
7	159.6	21	23.0	20.4
8	159.6	21	23.0	20.4
9	159.6	21	23.0	20.4
10	179.9	20	23.0	20.4
11	179.9	20	23.0	20.4
12	169.8	21	23.0	20.4

* Not all detectors set
** Adjusted Autoscope Speed

Lane Offset from Camera: 30.0 feet
(Lane No. 2)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1		21		
2	160.0	20	25.0	22.2
3	170.6	20	23.0	20.4
4	170.6	21	25.0	22.2
5	170.6	20	23.0	20.4
6	170.6	20	23.0	20.4
7	179.8	19	23.0	20.4
8	160.0	20	23.0	20.4
9	170.6	20	22.5	20.0
10	170.6	22	23.5	20.9
11				
12				

AUTOSCOPE TESTING DATA

Camera Height: 12.2 meters (40 feet) Vehicle Speed: 32 km/h (20 mph)

Lane Offset from Camera: 55.0 feet
(Lane No. 4)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1		20		
2	200.0	19	23.0	20.4
3	200.0	20	23.0	20.4
4	200.0	19	23.0	20.4
5	200.0	20	23.0	20.4
6	200.0	19	22.0	19.6
7	200.0	20	22.0	19.6
8	200.0	20	22.0	19.6
9	200.0	20	22.0	19.6
10	210.2	20	23.0	20.4
11	200.0	20	23.0	20.4
12	210.2	20	22.0	19.6

** Adjusted Autoscope Speed

Lane Offset from Camera: 67.5 feet
(Lane No. 5)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1		21		
2	199.8	21	24.0	21.3
3	190.0	21	24.0	21.3
4	260.3	20	24.0	21.3
5	199.8	20	24.0	21.3
6	190.0	20		
7	220.2	20	23.5	20.9
8	239.8	20	23.0	20.4
9	239.8	20	23.5	20.9
10	239.8	21	23.5	20.9
11	260.3	21	24.0	21.3
12	260.3	20	24.0	21.3

Lane Offset from Camera: 80.0 feet
(Lane no. 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1	399.9	20		
2	399.9	20	24.0	21.3
3	399.9	20	24.0	21.3
4	399.9	20	24.0	21.3
5	399.9	20	24.0	21.3
6	399.9	20	24.0	21.3
7	399.9	19	24.0	21.3
8	399.9	19	23.5	20.9
9	399.9	20	23.5	20.9
10	399.9	20	23.5	20.9
11				
12				

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/ Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1		21	25.0	22.2
2	359.4	21	25.0	22.2
3	399.9	22	25.5	22.7
4	359.4	21	25.5	22.7
5	359.4	20	25.5	22.7
6	359.4	20	24.5	21.8
7	399.9	20	24.0	21.3
8	359.4	20	24.0	21.3
9	359.4	20	24.0	21.3
10	399.9	21	24.0	21.3
11	399.9	21	24.5	21.8
12	359.4	20	25.5	22.7

** Adjusted Autoscope Speed

AUTOSCOPE TESTING DATA

Camera Height: 12.2 meters (40 feet) Vehicle Speed: 72 km/h (45 mph)

Lane Offset from Camera: 17.5 feet
(Lane No. 1)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	379.3	44	55.0	48.89
2	379.3	45	53.5	47.56
3	379.3	43	53.0	47.11
4	399.9	45	53.0	47.11
5	399.9	44	52.5	46.67
6	399.9	45	52.5	46.67
7	399.9	44	51.0	45.33
8	379.3	44	51.5	45.78
9	399.9	44	50.5	44.89
10	379.3	45	52.0	46.22
11	379.3	44	51.5	45.78
12		44	51.5	45.78

**Adjusted Autoscope Speed

Lane Offset from Camera: 30.0 feet
(Lane No. 2)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	400.6	44	50.5	44.89
2	400.6	44	51.5	45.78
3	379.8*	45	52.0	46.22
4	400.6	44	52.0	46.22
5	400.6	44	52.0	46.22
6	400.6	44	51.5	45.78
7	400.6	45	51.5	45.78
8	400.6	44	51.0	45.33
9	400.6	45	51.0	45.33
10	400.6	45	51.0	45.33
11	400.6	44	51.5	45.78
12	400.6	45	51.5	45.78

*Large cloud moved over study area affecting the detectors and background

Lane Offset from Camera: 55.0 feet
(Lane No. 4)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	399.8	44	51.0	45.33
2	399.8	42	49.5	44.00
3	399.8	43	51.0	45.33
4	399.8	45	51.0	45.33
5	399.8	45	52.0	46.22
6	399.8	45	52.0	46.22
7	399.8	44	51.0	45.33
8	399.8	44	51.0	45.33
9	399.8	45	51.5	45.78
10	399.8	43	52.0	46.22
11	399.8	44	49.0	43.56
12	399.8	45	50.0	44.44

**Adjusted Autoscope Speed

Lane Offset from Camera: 67.5 feet
(Lane No. 5)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	399.7	45	53.5	47.56
2	399.7	45	52.0	46.22
3	399.7	45	53.0	47.11
4	399.7	45	52.0	46.22
5	399.7	45		
6	399.7	45	51.0	45.33
7	399.7	45	51.0	45.33
8	399.7	43	49.0	43.56
9	399.7	45	48.0	42.67
10	399.7	45	49.0	43.56
11	399.7	44	49.0	43.56
12	399.7	44	49.0	43.56

AUTOSCOPE TESTING DATA

Camera Height: 12.2 meters (40 feet) Vehicle Speed: 72 km/h (45 mph)

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1	400.2	44	53.0	47.11
2	400.2	43	52.0	46.22
3	400.2	45	52.0	46.22
4	400.2	45	54.0	48.00
5	400.2	45	54.0	48.00
6	400.2	44	54.0	48.00
7	400.2	45	54.0	48.00
8	400.2	45	54.5	48.44
9	400.2	45	54.5	48.44
10	400.2	45	54.0	48.00
11	400.2	44	53.5	47.56
12	400.2	46	54.0	48.00

**Adjusted Autoscope Speed

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1	399.9	46	54.5	48.44
2	399.9	46	54.0	48.00
3	399.9	46	54.0	48.00
4	399.9	45	54.0	48.00
5	399.9	45	54.0	48.00
6	399.9	45	53.0	47.11
7	399.9	45	53.0	47.11
8	399.9	43	52.5	46.67
9	399.9	44	51.5	45.78
10	399.9	46	51.5	45.78
11	399.9	44	52.0	46.22
12	399.9	44	52.5	46.67

AUTOSCOPE TESTING DATA

Camera Height: 12.2 meters (40 feet) Vehicle Speed: 88 km/h (55 mph)

Lane Offset from Camera: 17.5 feet
(Lane No. 1)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1		51		
2	399.9	54	64.0	56.89
3	399.9	54	65.0	57.78
4	399.9	55	64.5	57.33
5	399.9	53	65.0	57.78
6	399.9	55	65.0	57.78
7	399.9	54	65.0	57.78
8	399.9	55	65.0	57.78
9	399.9	55	65.0	57.78
10	399.9	55	65.0	57.78
11	399.9	55	65.0	57.78
12	399.9	55	65.0	57.78

**Adjusted Autoscope speed

Lane Offset from Camera: 30.0 feet
(Lane No. 2)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.**
1	400.6	54	65.0	57.78
2	400.6	54	63.5	56.44
3	400.6	55	65.0	57.78
4	400.6	54	64.0	56.89
5	400.6	55	63.5	56.44
6	400.6	54	63.0	56.00
7	400.6	54	63.5	56.44
8	400.6	54	64.5	57.33
9	400.6	54	64.0	56.89
10	400.6	55	64.0	56.89
11	400.6	55	64.5	57.33
12	400.6	55	64.5	57.33

AUTOSCOPE TESTING DATA

Camera Height: 12.2 meters (40 feet) Vehicle Speed: 88 km/h (55 mph)

Lane Offset from Camera: 55.0 feet
(Lane No. 4)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	399.8	54	61.0	54.22
2	399.8	54	60.5	53.78
3	399.8	55	61.5	54.67
4	399.8	56	62.0	55.11
5	399.8	53	62.0	55.11
6	399.8	55	62.0	55.11
7	399.8	54	62.0	55.11
8	399.8	55	62.0	55.11
9	399.8	55	61.0	54.22
10	399.8	55	61.0	54.22
11	399.8	55	62.0	55.11
12	399.8	55	62.0	55.11

**Adjusted Autoscope speed

Lane Offset from Camera: 67.5 feet
(Lane No. 5)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	399.7	55	65.0	57.78
2	399.7	53	61.0	54.22
3	399.7	54	65.0	57.78
4	399.7	53	63.5	56.44
5	399.7	53	63.0	56.00
6	399.7	53	61.5	54.67
7	399.7	55	61.5	54.67
8	399.7	55	62.0	55.11
9	399.7	55	62.0	55.11
10	399.7	55	62.0	55.11
11	399.7	54	62.5	55.56
12	399.7	56		

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	400.2	54		
2	400.2	54	63.0	56.00
3	400.2	54	63.0	56.00
4	400.2	54	62.0	55.11
5	400.2	54	62.0	55.11
6	400.2	54	63.0	56.00
7	400.2	54	63.0	56.00
8	400.2	54	62.5	55.56
9	400.2	56	63.5	56.44
10	400.2	55	64.0	56.89
11	400.2	55	64.0	56.89
12	400.2	55	63.5	56.44

**Adjusted Autoscope speed

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/ Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	399.9	54	62.5	55.56
2	380.1*	55	64.5	57.33
3	380.1	55	63.0	56.00
4	380.1*	54	62.0	55.11
5	399.9	52	61.0	54.22
6	380.1	54	62.0	55.11
7	380.1	55	61.5	54.67
8	380.1	55	65.0	57.78
9	340.2	55	65.0	57.78
10	*	55	64.0	56.89
11	399.9	54	63.0	56.00
12	399.9	55	63.0	56.00

*Picture shifted

AUTOSCOPE TESTING DATA

Camera Height: 15.1 meters (49 feet 6 inches) Vehicle Speed: 32 km/h (20 mph)

Lane Offset from Camera: 17.5 feet
(Lane No. 1)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.**
1	210.1	23		
2	220.3	21	25.0	22.71
3	220.3	22		
4	210.1	21	24.5	22.25
5	230.0	21	24.0	21.80
6	220.3	21	24.0	21.80
7	220.3	20	2'.0	21.80
8	220.3	20	23.0	20.89
9	230.0	21	22.5	20.44
10	220.3	20	22.0	19.98
11	220.3	20	23.0	20.89
12	220.3	21	23.0	20.89
13	220.3		23.0	20.89

**Adjusted Autoscope Speed

Lane Offset from Camera: 30.0 feet
(Lane No. 2)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.**
1		20		
2	249.9	21	24.5	22.25
3	249.9	21	24.5	22.25
4	249.9	20	23.5	21.34
5	239.9	21	24.5	22.25
6	249.9	20	24.0	21.80
7	239.9	20	24.0	21.80
8	239.9	20	24.0	21.80
9	239.9	20	24.0	21.80
10	269.9	19		
11	249.9	21	23.5	21.34
12	239.9	21	25.0	22.71

Lane Offset from Camera: 55.0 feet
(Lane No. 4)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.**
1	230.0	20	25.0	22.71
2	230.0	20	23.0	20.89
3	230.0	20	23.0	20.89
4	230.0	20	23.0	20.89
5	230.0	21	23.0	20.89
6	230.0	20	23.0	20.89
7	240.2	20	23.0	20.89
8	230.0	20	23.0	20.89
9	230.0	21	23.0	20.89
10	230.0	20	23.0	20.89
11	279.9	20	23.5	21.34
12	230.0	20	23.5	21.34
13	230.0		23.0	20.89

**Adjusted Autoscope Speed

Lane Offset from Camera: 67.5 feet
(Lane No. 5)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.**
1	249.9*	19		
2	280.3	20	22.5	20.44
3	260.0	21	23.0	20.89
4	280.3	20	23.0	20.89
5	260.0	21	23.0	20.89
6	280.3	20	23.0	20.89
7	280.3	20	23.0	20.89
8	280.3	20	23.0	20.89
9	280.3	19	22.0	19.98
10	289.5	20	22.5	20.44
11		20	23.0	20.89
12	260.0	20	23.0	20.89

*Not all detectors set

AUTOSCOPE TESTING DATA

Camera Height: 15.1 meters (49 feet 6 inches) Vehicle Speed: 32 km/h (20 mph)

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.	100 ft.**
1	339.6	20	22.5	20.44
2	320.5	20	22.0	19.98
3	320.5	20	22.0	19.98
4	339.6	21	22.0	19.98
5	339.6	21	23.0	20.89
6	339.6	21	23.0	20.89
7	360.2	21	22.5	20.44
8	360.2	21	22.0	19.98
9	339.6	20	22.0	19.98
10	339.6	20	22.5	20.44
11	339.6	20	23.0	20.89
12	320.5	21	23.0	20.89

**Adjusted Autoscope Speed

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/ Occlusion)

Run Num.	Detector Location	Radar Speed (mph) 100 ft.	A-scope Speed (mph) 100 ft.	100 ft.**
1	330.0	19	18.5	16.80
2	330.0	21	23.5	21.34
3	330.0	20	22.0	19.98
4	330.0	20	22.0	19.98
5	330.0	20	22.0	19.98
6	330.0	21	23.0	20.89
7	400.1	20	23.0	20.89
8	330.0	20	22.5	20.44
9	330.0	20	22.0	19.98
10	330.0	20	22.0	19.98
11	330.0	20	22.0	19.98
12	330.0	20	22.5	20.44

AUTOSCOPE TESTING DATA

Camera Height: 15.1 meters (49 feet 6 inches) Vehicle Speed: 72 km/h (45 mph)

Lane Offset from Camera: 17.5 feet
(Lane No. 1)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	400.4	45	52.0	47.23
2	400.4	45	52.5	47.68
3	400.4	43	51.0	46.32
4	400.4	45	51.0	46.32
5	400.4	46	51.5	46.78
6	400.4	45	54.0	49.05
7	400.4	43	52.5	47.68
8	400.4	45	52.5	47.68
9	400.4	44	52.0	47.23
10	400.4	45	52.0	47.23
11	400.4	44	52.0	47.23
12	400.4	45	53.0	48.14

**Adjusted Autoscope Speed

Lane Offset from Camera: 30.0 feet
(Lane No. 2)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1		45		
2	400.5	45	53.0	48.14
3	400.5	45		
4	400.5	45	53.0	48.14
5	400.5	45	53.0	48.14
6	400.5	44	53.0	48.14
7	400.5	44	52.0	47.23
8	400.5	46	52.5	47.68
9	400.5	45	53.0	48.14
10	400.5	45	55.0	49.95
11	400.5	46	55.0	49.95
12	400.5	44		

AUTOSCOPE TESTING DATA

Camera Height: 15.1 meters (49 feet 6 inches) Vehicle Speed: 72 km/h (45 mph)

Lane Offset from Camera: 55.0 feet
(Lane No. 4)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	400.1	46	51.0	46.32
2	400.1	44	51.0	46.32
3	400.1	46	51.5	46.78
4	400.1	45	51.0	46.32
5	400.1	46	51.0	46.32
6	400.1	44	51.0	46.32
7	400.1	45	51.0	46.32
8	400.1	45	51.0	46.32
9	400.1	45	51.0	46.32
10	400.1	45	51.0	46.32
11	400.1	46	51.0	46.32
12	400.1	45	51.0	46.32

**Adjusted Autoscope Speed

Lane Offset from Camera: 67.5 feet
(Lane No. 5)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	399.9	45	57.0	51.77
2	399.9	44	52.0	47.23
3	399.9	44	51.0	46.32
4	399.9	45	53.0	48.14
5	399.9	46	54.0	49.05
6	399.9	46	53.5	48.59
7	399.9	45	53.0	48.14
8	399.9	44	52.5	47.68
9	399.9	45	52.0	47.23
10	399.9	45	52.0	47.23
11	399.9	45	55.0	49.95
12	399.9	45	56.0	50.86

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	400.0	44	49.0	44.50
2	400.0	45	50.5	45.87
3	400.0	46	50.5	45.87
4	400.0	45	50.5	45.87
5	400.0	45	50.0	45.41
6	400.0	45	46.0	41.78
7	400.0	45	46.0	41.78
8	400.0	43	46.0	41.78
9	400.0	44	45.0	40.87
10	400.0	45	45.0	40.87
11	400.0	45	45.0	40.87
12	400.0	45	49.0	44.50

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/ Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph) 100 ft.	Autoscope Speed (mph) 100 ft.	100 ft.**
1	400.5	45	52.5	47.68
2	400.5	44	53.0	48.14
3	400.5	45	53.0	48.14
4	400.5	46	53.0	48.14
5	400.5	46	53.0	48.14
6	400.5	45	53.0	48.14
7	400.5	45	53.0	48.14
8	400.5	45	53.0	48.14
9	400.5	44	53.0	48.14
10	400.5	45	53.0	48.14
11	400.5	45	52.5	47.68
12	400.5	44	52.0	47.23

**Adjusted Autoscope Speed

AUTOSCOPE TESTING DATA

Camera Height: 15.1 meters (49 feet 6 inches) Vehicle Speed: 88 km/h (55 mph)

Lane Offset from Camera: 17.5 feet
(Lane No. 1)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	400.4	55	62.5	56.77
2	400.4	55		
3	400.4	55	61.5	55.86
4	400.4	55	62.0	56.31
5	400.4	55	62.0	56.31
6	400.4	56	62.0	56.31
7	400.4	55	62.0	56.31
8	400.4	55	62.5	56.77
9	400.4	55	63.0	57.22
10	400.4	52	62.5	56.77
11	400.4	55	63.0	57.22
12	400.4	54	63.0	57.22

**Adjusted Autoscope Speed

Lane Offset from Camera: 30.0 feet
(Lane No. 2)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	400.5	55	64.5	58.58
2	400.5	55	64.5	58.58
3	400.5	55	65.0	59.04
4	400.5	55	66.0	59.94
5	400.5	55	66.0	59.94
6	400.5	55	65.0	59.04
7	400.5	55	65.0	59.04
8	400.5	55	64.0	58.13
9	400.5	55	64.0	58.13
10	400.5	54	64.0	58.13
11	400.5	55	64.0	58.13
12	400.5	54	64.0	58.13

Lane Offset from Camera: 55.0 feet
(Lane No. 4)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	400.0	54	61.5	55.86
2	400.0	54	62.0	56.31
3	339.9	55	63.5	57.67
4	400.0	54	63.5	57.67
5	400.0	54	62.0	56.31
6	400.0	55	62.0	56.31
7	400.0	55	62.0	56.31
8	400.0	55	62.0	56.31
9	400.0	55	62.0	56.31
10	400.0	54	62.0	56.31
11	400.0	55	62.0	56.31
12	400.0	55	62.0	56.31

**Adjusted Autoscope Speed

Lane Offset from Camera: 67.5 feet
(Lane No. 5)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	399.9	54	66	59.94
2	399.9	55		
3	399.9	55	63.66	57.82
4	399.9	54	64	58.13
5	399.9	55	64	58.13
6	399.9	55	62.66	56.91
7	399.9	55	62.39	56.67
8	399.9	54		
9	399.9	54	60.75	55.18
10	399.9	55		
11	399.9	54		
12	399.9	54		

AUTOSCOPE TESTING DATA

Camera Height: 15.1 meters (49 feet 6 inches) Vehicle Speed: 88 km/h (55 mph)

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/o Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	380.0*	55		
2	400.0	55	61.0	55.40
3	400.0	55	63.0	57.22
4	400.0	55	61.5	55.86
5	400.0	55	60.0	54.50
6	400.0	55	62.0	56.31
7	400.0	55	61.0	55.40
8	400.0	55	61.0	55.40
9	400.0	55	61.0	55.40
10	400.0	53	60.0	54.50
11	400.0	55	60.0	54.50
12	400.0	55	61.5	55.86

*Not all detectors set

**Adjusted Autoscope Speed

Lane Offset from Camera: 80.0 feet
(Lane No. 6 w/ Occlusion)

Run Num.	Detector Location (feet)	Radar Speed (mph)	Autoscope Speed (mph)	
		100 ft.	100 ft.	100 ft.**
1	400.5	53		
2	380.5*	54	61.0	55.40
3	380.5*	54	63.0	57.22
4	400.5	54	61.5	55.86
5	400.5	55	60.0	54.50
6	400.5	55	62.0	56.31
7	400.5	55	61.0	55.40
8	400.5	54	61.0	55.40
9	400.5	55	61.0	55.40
10	380.5*	55	60.0	54.50
11	400.5	55	60.0	54.50
12	400.5	54	61.5	55.86

*Video shifted

10.0 APPENDIX C

CALCULATED FIELD-OF-VIEW TABLES

Table C-1. Calculated Field-of-View Dimensions (f=6mm, 9.1 m Height)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
66.80	108.88	70	NA	81	NA	76	NA
68.20	110.27	75	NA	86	NA	81	NA
69.44	111.52	80	NA	91	NA	85	NA
70.56	112.63	85	NA	96	NA	90	NA
71.57	113.64	90	NA	101	NA	95	NA
72.47	114.55	95	NA	106	NA	100	NA
73.30	115.38	100	NA	111	NA	104	NA
74.05	116.13	105	NA	116	NA	109	NA
74.74	116.82	110	NA	122	NA	114	NA
75.38	117.45	115	NA	127	NA	119	NA
75.96	118.04	120	NA	132	NA	124	NA
76.50	118.58	125	NA	137	NA	129	NA
77.01	119.08	130	NA	142	NA	133	NA
77.47	119.55	135	NA	147	NA	138	NA
77.91	119.98	140	NA	153	NA	143	NA
78.31	120.39	145	NA	158	NA	148	NA
78.69	120.77	150	NA	163	NA	153	NA
79.05	121.12	155	NA	168	NA	158	NA
79.38	121.46	160	NA	173	NA	163	NA
79.70	121.77	165	NA	179	NA	168	NA
79.99	122.07	170	NA	184	NA	173	NA
80.27	122.35	175	NA	189	NA	178	NA
80.54	122.61	180	NA	194	NA	182	NA
80.79	122.86	185	NA	200	NA	187	NA
81.03	123.10	190	NA	205	NA	192	NA
81.25	123.33	195	NA	210	NA	197	NA
81.47	123.54	200	NA	216	NA	202	NA
81.67	123.75	205	NA	221	NA	207	NA
81.87	123.94	210	NA	226	NA	212	NA
82.06	124.13	215	NA	231	NA	217	NA
82.23	124.31	220	NA	237	NA	222	NA
82.41	124.48	225	NA	242	NA	227	NA
82.57	124.64	230	NA	247	NA	232	NA
82.72	124.80	235	NA	252	NA	237	NA
82.87	124.95	240	NA	258	NA	242	NA
83.02	125.09	245	NA	263	NA	247	NA
83.16	125.23	250	NA	268	NA	252	NA
83.29	125.37	255	NA	274	NA	257	NA
83.42	125.49	260	NA	279	NA	262	NA
83.54	125.62	265	NA	284	NA	267	NA
83.66	125.73	270	NA	289	NA	272	NA
83.77	125.85	275	NA	295	NA	277	NA
83.88	125.96	280	NA	300	NA	282	NA
83.99	126.07	285	NA	305	NA	287	NA
84.09	126.17	290	NA	311	NA	292	NA
84.19	126.27	295	NA	316	NA	297	NA

Table C-1. Calculated Field-of-View Dimensions (f=6mm, 9.1 m Height) (Continued)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
84.29	126.36	300	NA	321	NA	301	NA
84.38	126.46	305	NA	327	NA	306	NA
84.47	126.55	310	NA	332	NA	311	NA
84.56	126.63	315	NA	337	NA	316	NA
84.64	126.72	320	NA	343	NA	321	NA
84.73	126.80	325	NA	348	NA	326	NA
84.81	126.88	330	NA	353	NA	331	NA
84.88	126.96	335	NA	358	NA	336	NA
84.96	127.03	340	NA	364	NA	341	NA
85.03	127.11	345	NA	369	NA	346	NA
85.10	127.18	350	NA	374	NA	351	NA
85.17	127.24	355	NA	380	NA	356	NA
85.24	127.31	360	NA	385	NA	361	NA
85.30	127.38	365	NA	390	NA	366	NA
85.36	127.44	370	NA	396	NA	371	NA
85.43	127.50	375	NA	401	NA	376	NA
85.49	127.56	380	NA	406	NA	381	NA
85.54	127.62	385	NA	412	NA	386	NA
85.60	127.68	390	NA	417	NA	391	NA
85.66	127.73	395	NA	422	NA	396	NA
85.71	127.79	400	NA	427	NA	401	NA

Note: 1 meter = 3.28 feet; NA is offscale

Table C-2. Calculated Field-of-View Dimensions (f=6mm, 12.2 m Height)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
60.26	102.33	70	NA	86	NA	81	NA
61.93	104.00	75	NA	91	NA	85	NA
63.43	105.51	80	NA	95	NA	89	NA
64.80	106.87	85	NA	100	NA	94	NA
66.04	108.11	90	NA	105	NA	98	NA
67.17	109.24	95	NA	110	NA	103	NA
68.20	110.27	100	NA	115	NA	108	NA
69.15	111.22	105	NA	120	NA	112	NA
70.02	112.09	110	NA	125	NA	117	NA
70.82	112.90	115	NA	130	NA	122	NA
71.57	113.64	120	NA	135	NA	126	NA
72.26	114.33	125	NA	140	NA	131	NA
72.90	114.97	130	NA	145	NA	136	NA
73.50	115.57	135	NA	150	NA	141	NA
74.05	116.13	140	NA	155	NA	146	NA
74.58	116.65	145	NA	160	NA	150	NA
75.07	117.14	150	NA	165	NA	155	NA
75.53	117.60	155	NA	171	NA	160	NA
75.96	118.04	160	NA	176	NA	165	NA
76.37	118.45	165	NA	181	NA	170	NA
76.76	118.83	170	NA	186	NA	175	NA
77.12	119.20	175	NA	191	NA	180	NA
77.47	119.55	180	NA	196	NA	184	NA
77.80	119.87	185	NA	202	NA	189	NA
78.11	120.19	190	NA	207	NA	194	NA
78.41	120.48	195	NA	212	NA	199	NA
78.69	120.77	200	NA	217	NA	204	NA
78.96	121.03	205	NA	223	NA	209	NA
79.22	121.29	210	NA	228	NA	214	NA
79.46	121.54	215	NA	233	NA	219	NA
79.70	121.77	220	NA	238	NA	224	NA
79.92	121.99	225	NA	244	NA	229	NA
80.13	122.21	230	NA	249	NA	233	NA
80.34	122.42	235	NA	254	NA	238	NA
80.54	122.61	240	NA	259	NA	243	NA
80.73	122.80	245	NA	265	NA	248	NA
80.91	122.98	250	NA	270	NA	253	NA
81.09	123.16	255	NA	275	NA	258	NA
81.25	123.33	260	NA	280	NA	263	NA
81.42	123.49	265	NA	286	NA	268	NA
81.57	123.65	270	NA	291	NA	273	NA
81.72	123.80	275	NA	296	NA	278	NA
81.87	123.94	280	NA	301	NA	283	NA

Table C-2. Calculated Field-of-View Dimensions (f=6mm, 12.2 m Height) (Continued)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
82.01	124.09	285	NA	307	NA	288	NA
82.15	124.22	290	NA	312	NA	293	NA
82.28	124.35	295	NA	317	NA	298	NA
82.41	124.48	300	NA	323	NA	303	NA
82.53	124.60	305	NA	328	NA	308	NA
82.65	124.72	310	NA	333	NA	313	NA
82.76	124.84	315	NA	338	NA	318	NA
82.87	124.95	320	NA	344	NA	322	NA
82.98	125.06	325	NA	349	NA	327	NA
83.09	125.16	330	NA	354	NA	332	NA
83.19	125.27	335	NA	360	NA	337	NA
83.29	125.37	340	NA	365	NA	342	NA
83.39	125.46	345	NA	370	NA	347	NA
83.48	125.56	350	NA	375	NA	352	NA
83.57	125.65	355	NA	381	NA	357	NA
83.66	125.73	360	NA	386	NA	362	NA
83.75	125.82	365	NA	391	NA	367	NA
83.83	125.90	370	NA	397	NA	372	NA
83.91	125.99	375	NA	402	NA	377	NA
83.99	126.07	380	NA	407	NA	382	NA
84.07	126.14	385	NA	412	NA	387	NA
84.14	126.22	390	NA	418	NA	392	NA
84.22	126.29	395	NA	423	NA	397	NA
84.29	126.36	400	NA	428	NA	402	NA

Note: 1 meter = 3.28 feet; NA is offscale

Table C-3. Calculated Field-of-View Dimensions (f=8mm, 9.1 m Height)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
66.80	99.50	70	NA	61	NA	76	NA
68.20	100.90	75	NA	65	NA	81	NA
69.44	102.14	80	NA	68	NA	85	NA
70.56	103.26	85	NA	72	NA	90	NA
71.57	104.27	90	NA	76	NA	95	NA
72.47	105.17	95	NA	80	NA	100	NA
73.30	106.00	100	NA	84	NA	104	NA
74.05	106.75	105	NA	87	NA	109	NA
74.74	107.44	110	NA	91	NA	114	NA
75.38	108.08	115	NA	95	NA	119	NA
75.96	108.66	120	NA	99	NA	124	NA
76.50	109.20	125	NA	103	NA	129	NA
77.01	109.71	130	NA	107	NA	133	NA
77.47	110.17	135	NA	111	NA	138	NA
77.91	110.61	140	NA	115	NA	143	NA
78.31	111.01	145	NA	118	NA	148	NA
78.69	111.39	150	NA	122	NA	153	NA
79.05	111.75	155	NA	126	NA	158	NA
79.38	112.08	160	NA	130	NA	163	NA
79.70	112.40	165	NA	134	NA	168	NA
79.99	112.69	170	NA	138	NA	173	NA
80.27	112.97	175	NA	142	NA	178	NA
80.54	113.24	180	NA	146	NA	182	NA
80.79	113.49	185	NA	150	NA	187	NA
81.03	113.73	190	NA	154	NA	192	NA
81.25	113.95	195	NA	158	NA	197	NA
81.47	114.17	200	NA	162	NA	202	NA
81.67	114.37	205	NA	166	NA	207	NA
81.87	114.57	210	NA	170	NA	212	NA
82.06	114.76	215	NA	174	NA	217	NA
82.23	114.93	220	NA	178	NA	222	NA
82.41	115.11	225	NA	182	NA	227	NA
82.57	115.27	230	NA	186	NA	232	NA
82.72	115.42	235	NA	190	NA	237	NA
82.87	115.57	240	NA	193	NA	242	NA
83.02	115.72	245	NA	197	NA	247	NA
83.16	115.86	250	NA	201	NA	252	NA
83.29	115.99	255	NA	205	NA	257	NA
83.42	116.12	260	NA	209	NA	262	NA
83.54	116.24	265	NA	213	NA	267	NA
83.66	116.36	270	NA	217	NA	272	NA

Table C-3. Calculated Field-of-View Dimensions (f=8mm, 9.1 m Height) (Continued)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
83.77	116.47	275	NA	221	NA	277	NA
83.88	116.58	280	NA	225	NA	282	NA
83.99	116.69	285	NA	229	NA	287	NA
84.09	116.79	290	NA	233	NA	292	NA
84.19	116.89	295	NA	237	NA	297	NA
84.29	116.99	300	NA	241	NA	301	NA
84.38	117.08	305	NA	245	NA	306	NA
84.47	117.17	310	NA	249	NA	311	NA
84.56	117.26	315	NA	253	NA	316	NA
84.64	117.34	320	NA	257	NA	321	NA
84.73	117.43	325	NA	261	NA	326	NA
84.81	117.51	330	NA	265	NA	331	NA
84.88	117.58	335	NA	269	NA	336	NA
84.96	117.66	340	NA	273	NA	341	NA
85.03	117.73	345	NA	277	NA	346	NA
85.10	117.80	350	NA	281	NA	351	NA
85.17	117.87	355	NA	285	NA	356	NA
85.24	117.94	360	NA	289	NA	361	NA
85.30	118.00	365	NA	293	NA	366	NA
85.36	118.06	370	NA	297	NA	371	NA
85.43	118.13	375	NA	301	NA	376	NA
85.49	118.19	380	NA	305	NA	381	NA
85.54	118.24	385	NA	309	NA	386	NA
85.60	118.30	390	NA	313	NA	391	NA
85.66	118.36	395	NA	317	NA	396	NA
85.71	118.41	400	NA	321	NA	401	NA

Note: 1 meter = 3.28 feet; NA is offscale

Table C-4. Calculated Field-of-View Dimensions (f=8mm, 12.2 m Height)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
60.26	92.96	70	NA	64	NA	81	NA
61.93	94.63	75	NA	68	NA	85	NA
63.43	96.13	80	NA	72	NA	89	NA
64.80	97.50	85	NA	75	NA	94	NA
66.04	98.74	90	NA	79	NA	98	NA
67.17	99.87	95	NA	82	NA	103	NA
68.20	100.90	100	NA	86	NA	108	NA
69.15	101.85	105	NA	90	NA	112	NA
70.02	102.72	110	NA	94	NA	117	NA
70.82	103.52	115	NA	97	NA	122	NA
71.57	104.27	120	NA	101	NA	126	NA
72.26	104.96	125	NA	105	NA	131	NA
72.90	105.60	130	NA	109	NA	136	NA
73.50	106.20	135	NA	113	NA	141	NA
74.05	106.75	140	NA	116	NA	146	NA
74.58	107.28	145	NA	120	NA	150	NA
75.07	107.77	150	NA	124	NA	155	NA
75.53	108.23	155	NA	128	NA	160	NA
75.96	108.66	160	NA	132	NA	165	NA
76.37	109.07	165	NA	136	NA	170	NA
76.76	109.46	170	NA	140	NA	175	NA
77.12	109.82	175	NA	144	NA	180	NA
77.47	110.17	180	NA	148	NA	184	NA
77.80	110.50	185	NA	151	NA	189	NA
78.11	110.81	190	NA	155	NA	194	NA
78.41	111.11	195	NA	159	NA	199	NA
78.69	111.39	200	NA	163	NA	204	NA
78.96	111.66	205	NA	167	NA	209	NA
79.22	111.92	210	NA	171	NA	214	NA
79.46	112.16	215	NA	175	NA	219	NA
79.70	112.40	220	NA	179	NA	224	NA
79.92	112.62	225	NA	183	NA	229	NA
80.13	112.83	230	NA	187	NA	233	NA
80.34	113.04	235	NA	191	NA	238	NA
80.54	113.24	240	NA	195	NA	243	NA
80.73	113.43	245	NA	199	NA	248	NA
80.91	113.61	250	NA	203	NA	253	NA
81.09	113.79	255	NA	206	NA	258	NA
81.25	113.95	260	NA	210	NA	263	NA
81.42	114.12	265	NA	214	NA	268	NA
81.57	114.27	270	NA	218	NA	273	NA
81.72	114.42	275	NA	222	NA	278	NA
81.87	114.57	280	NA	226	NA	283	NA

Table C-4. Calculated Field-of-View Dimensions (f=8mm, 12.2 m Height) (Continued)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
82.01	114.71	285	NA	230	NA	288	NA
82.15	114.85	290	NA	234	NA	293	NA
82.28	114.98	295	NA	238	NA	298	NA
82.41	115.11	300	NA	242	NA	303	NA
82.53	115.23	305	NA	246	NA	308	NA
82.65	115.35	310	NA	250	NA	313	NA
82.76	115.46	315	NA	254	NA	318	NA
82.87	115.57	320	NA	258	NA	322	NA
82.98	115.68	325	NA	262	NA	327	NA
83.09	115.79	330	NA	266	NA	332	NA
83.19	115.89	335	NA	270	NA	337	NA
83.29	115.99	340	NA	274	NA	342	NA
83.39	116.09	345	NA	278	NA	347	NA
83.48	116.18	350	NA	282	NA	352	NA
83.57	116.27	355	NA	286	NA	357	NA
83.66	116.36	360	NA	290	NA	362	NA
83.75	116.45	365	NA	294	NA	367	NA
83.83	116.53	370	NA	298	NA	372	NA
83.91	116.61	375	NA	302	NA	377	NA
83.99	116.69	380	NA	306	NA	382	NA
84.07	116.77	385	NA	310	NA	387	NA
84.14	116.84	390	NA	314	NA	392	NA
84.22	116.92	395	NA	318	NA	397	NA
84.29	116.99	400	NA	322	NA	402	NA

Note: 1 meter = 3.28 feet; NA is offscale

Table C-5. Calculated Field-of-View Dimensions (f=10mm, 9.1 m Height)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
66.80	93.43	70	NA	49	NA	76	NA
68.20	94.82	75	NA	52	NA	81	NA
69.44	96.07	80	NA	55	NA	85	NA
70.56	97.18	85	NA	58	NA	90	NA
71.57	98.19	90	NA	61	NA	95	NA
72.47	99.10	95	NA	64	NA	100	NA
73.30	99.93	100	NA	67	NA	104	NA
74.05	100.68	105	NA	70	NA	109	NA
74.74	101.37	110	NA	73	NA	114	NA
75.38	102.00	115	NA	76	NA	119	NA
75.96	102.59	120	NA	79	NA	124	NA
76.50	103.13	125	NA	82	NA	129	NA
77.01	103.63	130	NA	85	NA	133	NA
77.47	104.10	135	NA	89	NA	138	NA
77.91	104.53	140	NA	92	NA	143	NA
78.31	104.94	145	NA	95	NA	148	NA
78.69	105.32	150	NA	98	NA	153	NA
79.05	105.67	155	NA	101	NA	158	NA
79.38	106.01	160	NA	104	NA	163	NA
79.70	106.32	165	NA	107	NA	168	NA
79.99	106.62	170	NA	111	NA	173	NA
80.27	106.90	175	NA	114	NA	178	NA
80.54	107.16	180	NA	117	NA	182	NA
80.79	107.41	185	NA	120	NA	187	NA
81.03	107.65	190	NA	123	NA	192	NA
81.25	107.88	195	NA	126	NA	197	NA
81.47	108.09	200	NA	129	NA	202	NA
81.67	108.30	205	NA	133	NA	207	NA
81.87	108.49	210	NA	136	NA	212	NA
82.06	108.68	215	NA	139	NA	217	NA
82.23	108.86	220	NA	142	NA	222	NA
82.41	109.03	225	NA	145	NA	227	NA
82.57	109.19	230	NA	148	NA	232	NA
82.72	109.35	235	NA	152	NA	237	NA
82.87	109.50	240	NA	155	NA	242	NA
83.02	109.64	245	NA	158	NA	247	NA
83.16	109.78	250	NA	161	NA	252	NA
83.29	109.92	255	NA	164	NA	257	NA
83.42	110.04	260	NA	168	NA	262	NA
83.54	110.17	265	NA	171	NA	267	NA
83.66	110.28	270	NA	174	NA	272	NA
83.77	110.40	275	NA	177	NA	277	NA
83.88	110.51	280	NA	180	NA	282	NA
83.99	110.62	285	NA	183	NA	287	NA

Table C-5. Calculated Field-of-View Dimensions (f=10mm, 9.1 m Height) (Continued)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
84.09	110.72	290	NA	187	NA	292	NA
84.19	110.82	295	NA	190	NA	297	NA
84.29	110.91	300	NA	193	NA	301	NA
84.38	111.01	305	NA	196	NA	306	NA
84.47	111.10	310	NA	199	NA	311	NA
84.56	111.18	315	NA	203	NA	316	NA
84.64	111.27	320	NA	206	NA	321	NA
84.73	111.35	325	NA	209	NA	326	NA
84.81	111.43	330	NA	212	NA	331	NA
84.88	111.51	335	NA	215	NA	336	NA
84.96	111.58	340	NA	219	NA	341	NA
85.03	111.66	345	NA	222	NA	346	NA
85.10	111.73	350	NA	225	NA	351	NA
85.17	111.79	355	NA	228	NA	356	NA
85.24	111.85	360	NA	231	NA	361	NA
85.30	111.93	365	NA	234	NA	366	NA
85.36	111.99	370	NA	238	NA	371	NA
85.43	112.05	375	NA	241	NA	376	NA
85.49	112.11	380	NA	244	NA	381	NA
85.54	112.17	385	NA	247	NA	386	NA
85.60	112.23	390	NA	250	NA	391	NA
85.66	112.28	395	NA	254	NA	396	NA
85.71	112.34	400	NA	257	NA	401	NA

Note: 1 meter = 3.28 feet; NA is offscale

Table C-6. Calculated Field-of-View Dimensions (f=10mm, 12.2 m Height)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
60.26	86.88	70	734	52	471	81	735
61.93	88.55	75	1583	54	1014	85	1583
63.43	90.06	80	NA	57	NA	89	NA
64.80	91.42	85	NA	60	NA	94	NA
66.04	92.66	90	NA	63	NA	98	NA
67.17	93.79	95	NA	66	NA	103	NA
68.20	94.82	100	NA	69	NA	108	NA
69.15	95.77	105	NA	72	NA	112	NA
70.02	96.64	110	NA	75	NA	117	NA
70.82	97.45	115	NA	78	NA	122	NA
71.57	98.19	120	NA	81	NA	126	NA
72.26	98.88	125	NA	84	NA	131	NA
72.90	99.52	130	NA	87	NA	136	NA
73.50	100.12	135	NA	90	NA	141	NA
74.05	100.68	140	NA	93	NA	146	NA
74.58	101.20	145	NA	96	NA	150	NA
75.07	101.69	150	NA	99	NA	155	NA
75.53	102.15	155	NA	102	NA	160	NA
75.96	102.59	160	NA	106	NA	165	NA
76.37	103.00	165	NA	109	NA	170	NA
76.76	103.38	170	NA	112	NA	175	NA
77.12	103.75	175	NA	115	NA	180	NA
77.47	104.10	180	NA	118	NA	184	NA
77.80	104.42	185	NA	121	NA	189	NA
78.11	104.74	190	NA	124	NA	194	NA
78.41	105.03	195	NA	127	NA	199	NA
78.69	105.32	200	NA	131	NA	204	NA
78.96	105.58	205	NA	134	NA	209	NA
79.22	105.84	210	NA	137	NA	214	NA
79.46	106.09	215	NA	140	NA	219	NA
79.70	106.32	220	NA	143	NA	224	NA
79.92	106.54	225	NA	146	NA	229	NA
80.13	106.76	230	NA	149	NA	233	NA
80.34	106.97	235	NA	153	NA	238	NA
80.54	107.16	240	NA	156	NA	243	NA
80.73	107.35	245	NA	159	NA	248	NA
80.91	107.53	250	NA	162	NA	253	NA
81.09	107.71	255	NA	165	NA	258	NA
81.25	107.88	260	NA	168	NA	263	NA
81.42	108.04	265	NA	172	NA	268	NA
81.57	108.20	270	NA	175	NA	273	NA
81.72	108.35	275	NA	178	NA	278	NA
81.87	108.49	280	NA	181	NA	283	NA

Table C-6. Calculated Field-of-View Dimensions (f=10mm, 12.2 m Height) (Continued)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
82.01	108.64	285	NA	184	NA	288	NA
82.15	108.77	290	NA	187	NA	293	NA
82.28	108.90	295	NA	191	NA	298	NA
82.41	109.03	300	NA	194	NA	303	NA
82.53	109.15	305	NA	197	NA	308	NA
82.65	109.27	310	NA	200	NA	313	NA
82.76	109.39	315	NA	203	NA	318	NA
82.87	109.50	320	NA	206	NA	322	NA
82.98	109.61	325	NA	210	NA	327	NA
83.09	109.71	330	NA	213	NA	332	NA
83.19	109.82	335	NA	216	NA	337	NA
83.29	109.92	340	NA	219	NA	342	NA
83.39	110.01	345	NA	222	NA	347	NA
83.48	110.11	350	NA	226	NA	352	NA
83.57	110.20	355	NA	229	NA	357	NA
83.66	110.28	360	NA	232	NA	362	NA
83.75	110.37	365	NA	235	NA	367	NA
83.83	110.45	370	NA	238	NA	372	NA
83.91	110.54	375	NA	241	NA	377	NA
83.99	110.62	380	NA	245	NA	382	NA
84.07	110.69	385	NA	248	NA	387	NA
84.14	110.77	390	NA	251	NA	392	NA
84.22	110.84	395	NA	254	NA	397	NA
84.29	110.91	400	NA	257	NA	402	NA

Note: 1 meter = 3.28 feet; NA is offscale

Table C-7. Calculated Field-of-View Dimensions (f=12mm, 9.1 m Height)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
66.80	89.30	70	2460	41	1319	76	2461
68.20	90.70	75	NA	43	NA	81	NA
69.44	91.94	80	NA	46	NA	85	NA
70.56	93.06	85	NA	48	NA	90	NA
71.57	94.07	90	NA	51	NA	95	NA
72.47	94.97	95	NA	53	NA	100	NA
73.30	95.80	100	NA	56	NA	104	NA
74.05	96.55	105	NA	59	NA	109	NA
74.74	97.24	110	NA	61	NA	114	NA
75.38	97.88	115	NA	64	NA	119	NA
75.96	98.46	120	NA	66	NA	124	NA
76.50	99.00	125	NA	69	NA	129	NA
77.01	99.51	130	NA	71	NA	133	NA
77.47	99.97	135	NA	74	NA	138	NA
77.91	100.41	140	NA	77	NA	143	NA
78.31	100.81	145	NA	79	NA	148	NA
78.69	101.19	150	NA	82	NA	153	NA
79.05	101.55	155	NA	85	NA	158	NA
79.38	101.88	160	NA	87	NA	163	NA
79.70	102.20	165	NA	90	NA	168	NA
79.99	102.49	170	NA	93	NA	173	NA
80.27	102.77	175	NA	95	NA	178	NA
80.54	103.04	180	NA	98	NA	182	NA
80.79	103.29	185	NA	100	NA	187	NA
81.03	103.53	190	NA	103	NA	192	NA
81.25	103.75	195	NA	106	NA	197	NA
81.47	103.97	200	NA	108	NA	202	NA
81.67	104.17	205	NA	111	NA	207	NA
81.87	104.37	210	NA	114	NA	212	NA
82.06	104.56	215	NA	116	NA	217	NA
82.23	104.73	220	NA	119	NA	222	NA
82.41	104.91	225	NA	122	NA	227	NA
82.57	105.07	230	NA	124	NA	232	NA
82.72	105.22	235	NA	127	NA	237	NA
82.87	105.37	240	NA	130	NA	242	NA
83.02	105.52	245	NA	132	NA	247	NA
83.16	105.66	250	NA	135	NA	252	NA
83.29	105.79	255	NA	138	NA	257	NA
83.42	105.92	260	NA	140	NA	262	NA
83.54	106.04	265	NA	143	NA	267	NA
83.66	106.16	270	NA	146	NA	272	NA
83.77	106.27	275	NA	148	NA	277	NA
83.88	106.38	280	NA	151	NA	282	NA
83.99	106.49	285	NA	154	NA	287	NA

Table C-7. Calculated Field-of-View Dimensions (f=12mm, 9.1 m Height) (Continued)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
84.09	106.59	290	NA	156	NA	292	NA
84.19	106.69	295	NA	159	NA	297	NA
84.29	106.79	300	NA	162	NA	301	NA
84.38	106.88	305	NA	164	NA	306	NA
84.47	106.97	310	NA	167	NA	311	NA
84.56	107.06	315	NA	170	NA	316	NA
84.64	107.14	320	NA	172	NA	321	NA
84.73	107.23	325	NA	175	NA	326	NA
84.81	107.31	330	NA	178	NA	331	NA
84.88	107.38	335	NA	180	NA	336	NA
84.96	107.46	340	NA	183	NA	341	NA
85.03	107.53	345	NA	186	NA	346	NA
85.10	107.60	350	NA	188	NA	351	NA
85.17	107.67	355	NA	191	NA	356	NA
85.24	107.74	360	NA	194	NA	361	NA
85.30	107.80	365	NA	196	NA	366	NA
85.36	107.86	370	NA	199	NA	371	NA
85.43	107.93	375	NA	202	NA	376	NA
85.49	107.99	380	NA	204	NA	381	NA
85.54	108.04	385	NA	207	NA	386	NA
85.60	108.10	390	NA	210	NA	391	NA
85.66	108.16	395	NA	212	NA	396	NA
85.71	108.21	400	NA	215	NA	401	NA

Note: 1 meter = 3.28 feet; NA is offscale

Table C-8. Calculated Field-of-View Dimensions (f=12mm, 12.2 m Height)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
60.26	82.76	70	315	43	170	81	317
61.93	84.43	75	410	46	221	85	412
63.43	85.93	80	563	48	302	89	564
64.80	87.30	85	848	50	455	94	849
66.04	88.54	90	1567	53	840	98	1567
67.17	89.67	95	6869	55	3681	103	6869
68.20	90.70	100	NA	58	NA	108	NA
69.15	91.65	105	NA	60	NA	112	NA
70.02	92.52	110	NA	63	NA	117	NA
70.82	93.32	115	NA	65	NA	122	NA
71.57	94.07	120	NA	68	NA	126	NA
72.26	94.76	125	NA	70	NA	131	NA
72.90	95.40	130	NA	73	NA	136	NA
73.50	96.00	135	NA	75	NA	141	NA
74.05	96.55	140	NA	78	NA	146	NA
74.58	97.08	145	NA	81	NA	150	NA
75.07	97.57	150	NA	83	NA	155	NA
75.53	98.03	155	NA	86	NA	160	NA
75.96	98.46	160	NA	88	NA	165	NA
76.37	98.87	165	NA	91	NA	170	NA
76.76	99.26	170	NA	94	NA	175	NA
77.12	99.62	175	NA	96	NA	180	NA
77.47	99.97	180	NA	99	NA	184	NA
77.80	100.30	185	NA	101	NA	189	NA
78.11	100.61	190	NA	104	NA	194	NA
78.41	100.91	195	NA	107	NA	199	NA
78.69	101.19	200	NA	109	NA	204	NA
78.96	101.46	205	NA	112	NA	209	NA
79.22	101.72	210	NA	115	NA	214	NA
79.46	101.96	215	NA	117	NA	219	NA
79.70	102.20	220	NA	120	NA	224	NA
79.92	102.42	225	NA	122	NA	229	NA
80.13	102.63	230	NA	125	NA	233	NA
80.34	102.84	235	NA	128	NA	238	NA
80.54	103.04	240	NA	130	NA	243	NA
80.73	103.23	245	NA	133	NA	248	NA
80.91	103.41	250	NA	136	NA	253	NA
81.09	103.59	255	NA	138	NA	258	NA
81.25	103.75	260	NA	141	NA	263	NA
81.42	103.92	265	NA	144	NA	268	NA
81.57	104.07	270	NA	146	NA	273	NA
81.72	104.22	275	NA	149	NA	278	NA
81.87	104.37	280	NA	152	NA	283	NA

Table C-8. Calculated Field-of-View Dimensions (f=12mm, 12.2 m Height) (Continued)

Angle 1	Angle 2	Near Pvmt. 1	Far Pvmt. 2	H. FOV 1	H. FOV2	Hyp. 1	Hyp. 2
82.01	104.51	285	NA	154	NA	288	NA
82.15	104.65	290	NA	157	NA	293	NA
82.28	104.78	295	NA	160	NA	298	NA
82.41	104.91	300	NA	162	NA	303	NA
82.53	105.03	305	NA	165	NA	308	NA
82.65	105.15	310	NA	168	NA	313	NA
82.76	105.26	315	NA	170	NA	318	NA
82.87	105.37	320	NA	173	NA	322	NA
82.98	105.48	325	NA	175	NA	327	NA
83.09	105.59	330	NA	178	NA	332	NA
83.19	105.69	335	NA	181	NA	337	NA
83.29	105.79	340	NA	183	NA	342	NA
83.39	105.89	345	NA	186	NA	347	NA
83.48	105.98	350	NA	189	NA	352	NA
83.57	106.07	355	NA	191	NA	357	NA
83.66	106.16	360	NA	194	NA	362	NA
83.75	106.25	365	NA	197	NA	367	NA
83.83	106.33	370	NA	199	NA	372	NA
83.91	106.41	375	NA	202	NA	377	NA
83.99	106.49	380	NA	205	NA	382	NA
84.07	106.57	385	NA	207	NA	387	NA
84.14	106.64	390	NA	210	NA	392	NA
84.22	106.72	395	NA	213	NA	397	NA
84.29	106.79	400	NA	215	NA	402	NA

Note: 1 meter = 3.28 feet; NA is offscale