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16. Abstract

The primary objective of this research was to validate the new TxDOT procedures for loop detector placement on high-speed approaches to signalized intersections. The study approach involved conducting a field study at selected sites to compare the proposed new loop configuration to the existing configuration. The data analysis included investigating approach speeds to the intersection, driver actions in response to a yellow indication, and vehicle location at the onset of yellow.

The results from the field study revealed that the new loop configuration is as good as, and in some cases better than, the old loop configuration. Because the new loop configuration can detect vehicles further upstream from the intersection (at the beginning of the dilemma zone), it results in fewer vehicles being caught in the dilemma zone at the onset of yellow. Also, because the new loop configuration typically resulted in more vehicles running the yellow light instead of stopping, fewer rear-end accidents may result. In addition, the new loop configuration resulted in fewer vehicles running the red light, also a major cause of accidents.

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GUIDELINES FOR DETECTOR PLACEMENT ON HIGH-SPEED APPROACHES TO SIGNALIZED INTERSECTIONS

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IMPLEMENTATION STATEMENT

TxDOT's new procedures for detector placement address all high-speed approaches from 72 km/h (45 mph) to 113 km/h (70 mph). The results of this research indicate that the new TxDOT detector placement performs as expected in detection of vehicles at much greater distances from the intersection. This provides more distance (or time) to make the appropriate decision upon the onset of yellow, then red. The new detector placement plan has already been implemented in a few districts where 113 km/h (70 mph) approaches exist. With the successful outcome of this project, this detector scheme should be implemented elsewhere at intersections which are otherwise safe for these speeds. Based on the findings from this study, it is recommended that the detector layout be based on the 85^{th} percentile approach speed to the intersection (as opposed to the posted speed limit). Deliverables for this project include a standard sheet for implementation of the new detector layout on future construction projects.

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT). This is only a TxDOT report. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The principal investigator for the project was Dan Middleton, P.E. #60764.

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SUMMARY

The restoration of the 113 km/h (70 mph) speed limit in Texas has created a concern for signalized intersections with the higher approach speeds. Current TxDOT recommended procedures do not address approach speeds above 89 km/h (55 mph), and therefore, the high-speed approach intersections may not have adequate *dilemma zone* detection. TxDOT has developed a new procedure for detector placement which addresses all high-speed approaches 72 to 113 km/h (45 to 70 mph).

The primary objective of this research was to validate the new TxDOT procedures for loop detector placement on high-speed approaches to signalized intersections. The goal of the new procedures is to increase the safety at high-speed approach intersections above that of existing procedures. The study approach involved the following five main tasks: literature search and review, survey of other state practices, data collection at existing field sites with high-speed approaches, data analysis, and development of recommendations.

The field study involved conducting a before/after analysis at selected field sites to compare the proposed new loop configuration to the existing configuration. The data analysis included investigating approach speeds to the intersection, driver actions in response to a yellow indication, and vehicle location at the onset of yellow.

The results from the field study revealed that the new loop configuration is as good as, and in some cases better than, the old loop configuration. Because the new loop configuration can detect vehicles further upstream from the intersection (at the beginning of the dilemma zone), it results in fewer vehicles being caught in the dilemma zone at the onset of yellow. Also, because the new loop configuration typically resulted in more vehicles running the yellow light instead of stopping, fewer rear-end accidents may result. In addition, the new loop configuration resulted in fewer vehicles running the red light, also a major cause of accidents.

The new detector placement plan has already been implemented in a few districts where 113 km/h (70 mph) approaches exist. Based on the findings from this study, the researchers recommend that the new procedures for loop detector placement should be implemented elsewhere at intersections which are otherwise safe for these speeds. In addition, it is recommended that the detector layout be based on the 85th percentile approach speed to the intersection (as opposed to the posted speed limit).

1.0 INTRODUCTION AND REVIEW OF EXISTING PRACTICES

1.1 OVERVIEW

The restoration of the 113 km/h (70 mph) speed limit in Texas has created a concern for signalized intersections with the higher approach speeds. TxDOT-recommended procedures do not address approach speeds above 89 km/h (55 mph), and therefore, the high-speed approach intersections may not have adequate dilemma zone detection. The term dilemma zone refers to either a physical segment of the intersection approach, or it can be defined in terms of the decision-making process. The "physical segment" refers to a physical length of the approach in which a driver cannot go through the intersection or stop legally. The "decision-making" definition refers to the area where the probability of drivers attempting to stop is between 10 and 90 percent. TxDOT has developed a new procedure for detector placement which addresses all high-speed approaches 72 to 113 km/h (45 to 70 mph). Two TxDOT districts are field testing the recommended procedure and are preparing plans for intersections with 113 km/h (70 mph) approaches.

The problem at hand concerns traffic-actuated control in which demand varies throughout the day or main street traffic is heavier than side street traffic. The quality of service provided by the controller/detector system is dependent upon three items: 1) controller settings, 2) detector unit operation, and 3) detector layout. The third item is the primary subject matter of this research. Optimum performance of the detector layout requires a detector design "tuned" to the geometry of the intersection and its traffic demand. It should also be noted that the detector of choice is still the inductive loop detector (ILD), although other detection technologies such as video imaging could also be used. However, the increased detection distances of 183 m (600 feet) or more required for high-speed approaches challenges the currently available products using the typically available camera optics and mounting heights.

This research study evaluated the new recommended procedure to ensure that it accomplishes the intended goal of providing adequate safety at high-speed approach intersections. The new procedure, if successful, will be implemented state-wide for intersections with high-speed approaches.

1.2 RESEARCH FOCUS

This research study focused on maximizing traffic safety as opposed to emphasizing efficiency on high-speed approaches, even though efficiency is still an important topic to be considered. Efficiency is not the critical issue since high speed approaches (especially 113 km/h (70 mph)) are typically found in more rural settings where capacity is not the primary concern. In general, detector designs which avoid the onset of yellow when the intersection approach is occupied are less likely to be associated with rear-end crashes. In this context, it should be noted that there are differences in driver responses to the onset of the yellow indication. With two or more drivers on an approach presented with the yellow, it is likely that some drivers will decide to stop while others will continue through the intersection. These conflicting responses create the potential for rear-end crashes when stopping drivers are ahead of those choosing to proceed. There is also the potential for right-angle crashes within the intersection for vehicles proceeding through upon the onset of the yellow.

1.3 RESEARCH OBJECTIVES

The work plan for this study initially consisted of six specific research objectives including: a literature search and review, survey of other state practices, data collection at high-speed approaches, data analysis, simulation of selected speed categories, and preparation of reports. However, a modification of the study eliminated the simulation of selected speed categories and replaced it with additional field data collection.

1.4 METHODOLOGY

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

1.4.1 Literature Search and Review

A comprehensive literature search, which is fundamental for any research project, identified publications and reports on state-of-the-art technologies and current knowledge concerning traffic signal detector placement, high speed intersections, and dilemma zones. This search, using key words and phrases, utilized the following catalogs and databases: Texas A&M University's Sterling C. Evans Library NOTIS (local library database), Wilson's Periodical Database, FirstSearch, National Technical Information System (NTIS), and Transportation Research Information Service (TRIS). The research team identified approximately 175 as possible sources and reviewed them for relevance Section 1.6 of this chapter discusses the literature review.

1.4.2 Survey of Other States

Researchers identified several states through the literature search process and from the knowledge of project staff. The TTI research team conducted a telephone survey with a number of these states. The survey included questions about the procedures used in each state and quality of the data used for evaluation. Section 1.6 of this chapter discusses the survey of states.

1.4.3 Data Collection at High-Speed Approaches

The primary goal of this research study was to validate the new TxDOT procedures for high-speed approaches for speeds from 70 km/h (45 mph) through 113 km/h (70 mph). TxDOT provided support for TTI data collection at four intersections with 113 km/h (70 mph) approach speeds for field data collection: three in the Houston district and one in the Odessa district. A fifth intersection, located in the Brownwood district with a 89 km/h (50 mph) speed limit, was included in the crash analysis portion. The primary interest in the field data collection activity was determining whether dilemma zone protection is adequate and how it compares with procedures used today for slower approach speeds. The goal of the new procedures is increasing the safety at high speed approach intersections above that of existing procedures. Data collection for accomplishing this evaluation was directed at both vehicle crashes and erratic maneuvers in a before/after study scenario. Given the short duration of the study plus the fact that speed limits were recently increased, availability of crash data during both the "before" and "after" periods (constant speed limit) were limited. The typical delay involved in accident record keeping also limited the "after" data.

The field data collection portion of this research took a two-pronged approach. The first step was to evaluate the performance of the detector system as vehicles approach the intersection. The second step included an evaluation of how well the overall signal system (including detectors) performed in terms of dilemma zone protection.

For monitoring conflicts at study sites, research staff utilized color video cameras to monitor high speed approaches during the data collection phase. For this task, technicians mounted a camera on a trailer equipped with a telescoping pole that can be extended up to 9.1 m (30 ft). This required visible "targets" along the pavement to help data reducers determine exact locations of detectors and limits of the dilemma zone during video replay. Chapter 2 provides a description of the data collection efforts.

1.4.4 Data Analysis

The data analysis included investigating approach speeds to the intersection, driver actions in response to a yellow indication, and vehicle location at the onset of yellow. The evaluation followed a "before-after" scenario in which the existing (assumed to be 89 km/h [55 mph]) detector placement and signal timing plan represented the "before" period. Once sufficient data were collected under the existing situation, the study team evaluated the proposed TxDOT detector placement. Data collection followed a statistically sound plan in order to make an accurate comparison from the "before" to "after" scenarios. Evaluation used the t-test and chi-square test to study driver actions and vehicle locations within the dilemma zone. For the crash rate analysis, the original intent was to research statistically significant changes in crash rates or severity between the "before" and "after" time periods. However, a lack of data limited evaluation. Chapter 2 gives a summary of the results from the field studies.

1.5 EXISTING PRACTICES

Researchers identified existing procedures and practices involving detector placement at high-speed approaches to signalized intersections through a review of literature and a survey of state agencies. Following is a summary of these results.

1.5.1 Literature Review

An examination of the literature revealed that there is a broad range of design philosophies being used for detector placement. Some agencies locate each advance detector based on stopping sight distance for a specified design speed. The design speed is decreased by 16 km/h (10 mph) for each successive detector on the approach. Other agencies locate detectors based on having a constant travel time between successive detector pairs. Some agencies choose to extend the green until the vehicle is fully within the intersection. Other agencies prefer to extend the green until the vehicle clears its dilemma zone. Yet other agency approaches vary based on controller options (e.g., locking versus non-locking memory).

As previously noted, the dilemma zone is a term that refers to either a physical segment of the intersection approach or the decision-making process. In both early and current research on dilemma zones, there is some disagreement as to the location of the dilemma zone boundaries. Some of this disparity can be explained by differences in driver/vehicle populations at the various test sites. A recent study by Bonneson et al. *(1, 2)* noted a trend toward increased length of dilemma zone boundaries compared to older study findings. It suggested that the reason for the increase is a trend toward decreasing driver respect for the change interval.

In the early dilemma zone analyses, Parsonson et al. *(3)* examined and summarized existing research on the probability of stopping from various speeds *(4, 5, 6)*. Comparison of data collected by Zegeer of the Kentucky Department of Transportation *(7)* revealed that his dilemma zones (10 and 90 percent probabilities of stopping) were 28 to 38 percent longer than those measured by Parsonson et al. *(8)* for speeds of 72 to 80 km/h (45 to 50 mph). Since Zegeer's data were collected under closely controlled conditions, many practitioners have used his data.

Zegeer *(7)*, using the parameter of passage time, found that 5 seconds was sufficient for vehicles to travel from the initial upstream detector to the intersection for speeds below 97 km/h (60 mph). Other methods used before these analyses involved kinematic analyses of either stopping or clearing the stop bar. Some early investigators used AASHTO (then AASHO) minimum stopping sight distances, while others used a one second driver reaction time and an emergency stop on dry pavement *(9)*. One of the detector-controller design scenarios that looked very promising to these investigators used a green extension system, apparently similar to that used today but probably more primitive. One example used a 21 m (70 ft) loop detector at the stop bar for normal detector output supplemented by an extended call detector 5 seconds before the stop bar. Zegeer *(7)* reported on the effectiveness of five locations in Kentucky, concluding that there was an overall crash reduction of approximately 50 percent compared to previously used detection scenarios. Another parameter measured by Zegeer in dilemma zone studies was traffic conflicts *(10)*. In studies before and after installation of green-phase extension systems (GES), he used the following six types of conflicts: red light runs, abrupt stops, swerve to avoid collision, vehicle skidded, acceleration through yellow, and brakes applied before passing through the intersection. Zegeer's findings included reductions in conflicts at two test sites with the use of GES. Mean values of conflict rates reduced from 4.34 to 2.64 conflicts per 15-minute interval at one site and from 4.22 to 0.66 at another site.

In a recent ITE Journal article entitled, "Traffic Detector Designs for Isolated Intersections," Bonneson and McCoy *(1)* provide some insights based on their recent research on detector design *(2)*. They stated that the overall objective in properly designing detection at actuated high-speed approaches is to minimize delay without compromising safety. This is typically accomplished by proper coordination of detector size and location with the various timing features of the detector unit and controller. The authors discuss dilemma zone protection and describe it as the prevention of phase termination while a vehicle is in the dilemma zone. This protection may be achieved by strategically locating detectors on the intersection approach and adjusting the detector unit settings such that a vehicle can "hold" the green while it travels through the dilemma zone. As vehicles approach the dilemma zone, drivers face a decision upon onset of yellow to either stop or proceed through the intersection. Intuition suggests a correlation between the number of vehicular crashes (typically rear-end) and frequency of "maxout." This is primarily due to a leading vehicle that attempts to stop followed by a vehicle in the same lane that attempts to proceed. The authors promote the idea of dilemma zone protection through proper design of advance detectors.

Woods and Koniki, in a final report entitled, Optimizing Detector Placement for High Speed Isolated Signalized Intersections Using Vehicular Delay as the Criterion, *(11)* noted a negative aspect of providing dilemma zone protection. On high speed approaches to an isolated intersection, providing dilemma zone protection may result in sluggish operations and possibly higher delays. A trade-off analysis of detector placement is essential for optimization of dilemma zone protection and reducing delays. They utilized the TEXAS Model (Version 3.2) to determine optimal detector placement strategies on high speed isolated intersections. Traffic volumes varied between 200 vehicles per hour per approach to 800 vehicles per hour per approach. Mean speeds of 89 km/h (55 mph), 72 km/h (45 mph), and 56 km/h (35 mph) were simulated. Detector placements were developed for both the mean and 85th percentile speeds.

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

1.5.2 Survey of Existing Practices

The research team conducted a telephone survey was conducted to determine policies in use for high speed loop detection at signalized intersections. The 14 states contacted were selected based upon Internet chat information, knowledge of states with speed limits greater than 97 km/h (60 mph), states that have long sections of open highway where high speed approaches are not uncommon, and personal contacts of the researchers. Contacts included state traffic engineers and engineers responsible for traffic signal systems. Respondents were asked a series of questions related to loop detector placement for high-speed approaches.

As indicated in Table 1-1, nine of the 14 states contacted have a policy or procedure for loop detector placement at high speed approaches. However, several of the policies do not include ILD spacings for speeds greater than 89 or 97 km/h (55 or 60 mph), and many of the states indicated that they try to avoid signalized approaches at 97 km/h (55 mph) or greater. For example, Wyoming drops the speed limit to 72 km/h (45 mph) at intersections when a traffic signal is installed. Alternately, states such as Washington have isolated signals posted at speeds of 89 km/h (55 mph) or greater and have a policy with a variable number of loops based upon 90th percentile speed, perception reaction times, and deceleration rates. Policies and procedures vary from state to state, and Table 1-1 provides a brief summary of these policies.

Table 1-1. Summary of Telephone Survey.

STATE	POLICY / PROCEDURE FOR HIGH-SPEED DETECTION	COMMENTS
Arizona	Yes	Not used for high speeds; most approaches at 72 km/h (45 mph) or less. Placement based on February 1974 issue of *Traffic Engineering* article "Small Area Detection at Intersection Approaches."
California	Yes	Loop placement based on deceleration rate for dry condition.
Kentucky	Yes	Green Extension System for isolated signals or first in a series with 85th percentile speed ≥ 72 km/h (45 mph). Set of 2 loops with distances based on approach grades.
Maryland	Yes	No arterial or surface streets > 97 km/h (60 mph). Use a dilemma zone chart.
Minnesota	Yes	Based on design and operational requirements. Currently no intersections signed > 89 km/h (55 mph). Detector placement based on dilemma zone chart.
Missouri	Yes	85th percentile speed≥ 72 km/h (45 mph); new guideline in trial period. Two pulse detectors at 8 seconds and 5 seconds back from stop bar.
Montana	No	Although the daytime speed limit is 'reasonable and prudent' with no limit for passenger cars, they try to avoid high-speed approaches.
Nebraska	Yes	Approach speed up to 97 km/h (60 mph); 3 detectors based on 2-second extension.
New Jersey	No	No speed limits > 89 km/h (55 mph).
Ohio	Yes	For approach speeds from 64 - 97 km/h (40 - 60 mph), use 2 loops with placement based on approach speed.
Oklahoma	No	N / A
Tennessee	No	Do not have a written policy but use a standard loop placement procedure for speeds > 72 km/h (45 mph).
Washington	Yes	Procedure based on 90th percentile speeds for upstream dilemma zones and 10th percentile speeds for downstream dilemma zones, perception-reaction times, and deceleration rates. Number of loops varies.
Wyoming	No	Currently no signals greater than 72 km/h (45 mph), although they do have guides for 80 and 89 km/h (50 and 55 mph).

2.0 FIELD STUDIES

2.1 INTRODUCTION

The primary objective of this research was to validate the new TxDOT procedures for loop detector placement on high-speed approaches to signalized intersections. The goal of the new procedures was to increase the safety at high-speed approach intersections above that of existing procedures. The focus of the data collection activity was to determine whether the new procedures provide adequate dilemma zone protection and how the protection from the new procedures compare with existing procedures used today.

Data collection for accomplishing this evaluation focused on driver behavior and vehicle crashes using a before/after study scenario. Given the short duration of the study plus the fact that speed limits were only recently increased, availability of crash data during both the "before" and "after" periods were limited. The typical delay involved in accident record keeping also limited the "after" data. The study team, nonetheless, attempted to collect, evaluate, and apply statistical analyses to crash data as appropriate.

The field data collection portion of this research involved two steps. The first step was to evaluate the performance of the detector system as vehicles approached the intersection. The second step included an evaluation of how well the overall signal system (including detectors) performed in terms of dilemma zone protection. The following sections describe the data collection, data reduction, and data analysis techniques.

2.2 DATA COLLECTION

2.2.1 Equipment

The research team used a wide array of data collection equipment to collect the data necessary for this research. One of TTI's data collection trailers provided mounting support for a Cohu charged couple display (CCD) camera raised via a telescoping pole to a height of 9.1 m (30 ft). The camera's focal length varied from 6 mm to 60 mm, and a field technician utilized its pan/tilt/zoom control from ground level to establish optimum settings. The trailer's location at each field site was approximately 300 m (1000 ft) from the intersection under analysis. From this perspective, the camera provided a large area view around each intersection. It allowed monitoring the signal indications and actions by drivers over a distance of approximately 244 m (800 ft) of the approach to the intersection. Figure 2-1 is a photograph of the TTI video trailer.

Figure 2-1. Camera Mounted on Telescoping Pole.

At each of the sites selected to be analyzed, vehicle detection for the signalized intersection occurred through the use of inductive loops detectors (ILDs). Four of the five sites had existing ILDs configured for approach speeds of 89 km/h (55 mph) using the old TxDOT procedure for loop detector placement. TxDOT had already installed its new detector layout at the Odessa site prior to TTI's data collection. Therefore, to conduct the before/after study, TTI's field team installed the old detector layout using temporary ILDs, which would have represented the 89 km/h (55 mph) detector spacing. These temporary ILDs used three turns of 14 gauge wire and a road tape material called Polyguard. Leads connecting ILDs with the cabinet were also 14 gauge wire. Table 2-1 summarizes the distances from the stop bar of existing loops (89 km/h [55 mph]) and new loops (113 km/h [70 mph]).

The field data collection plan also included two classifiers from International Road Dynamics (IRD) for monitoring and recording speeds of each vehicle at 107 m (350 ft) from the stop bar and at 183 m (600 ft) from the stop bar. Detection for each of the classifiers required two piezoelectric sensors placed 3.0 m (10 ft) apart and one temporary ILD in each lane. The sequence was piezo-loop-piezo as shown by Figure 2-2. It should be noted that both old and new procedures also required a presence loop at the stop bar. Figure 2-3 shows the layout of the equipment for a typical intersection. All distances are referenced to the stop line.

Table 2-1. Placement of ILDs for Old and New Procedure (Distance from Stop Bar).

Old Procedure (89 km/h [55 mph])	New Procedure (113 km/h [70 mph])
24 m (80 ft)	107 m (350 ft)
43 m (140 ft)	145 m (475 ft)
67 m (220 ft)	183 m (600 ft)
98 m (320 ft)	

Figure 2-2. Temporary Inductive Loop and Piezoelectric Sensors.

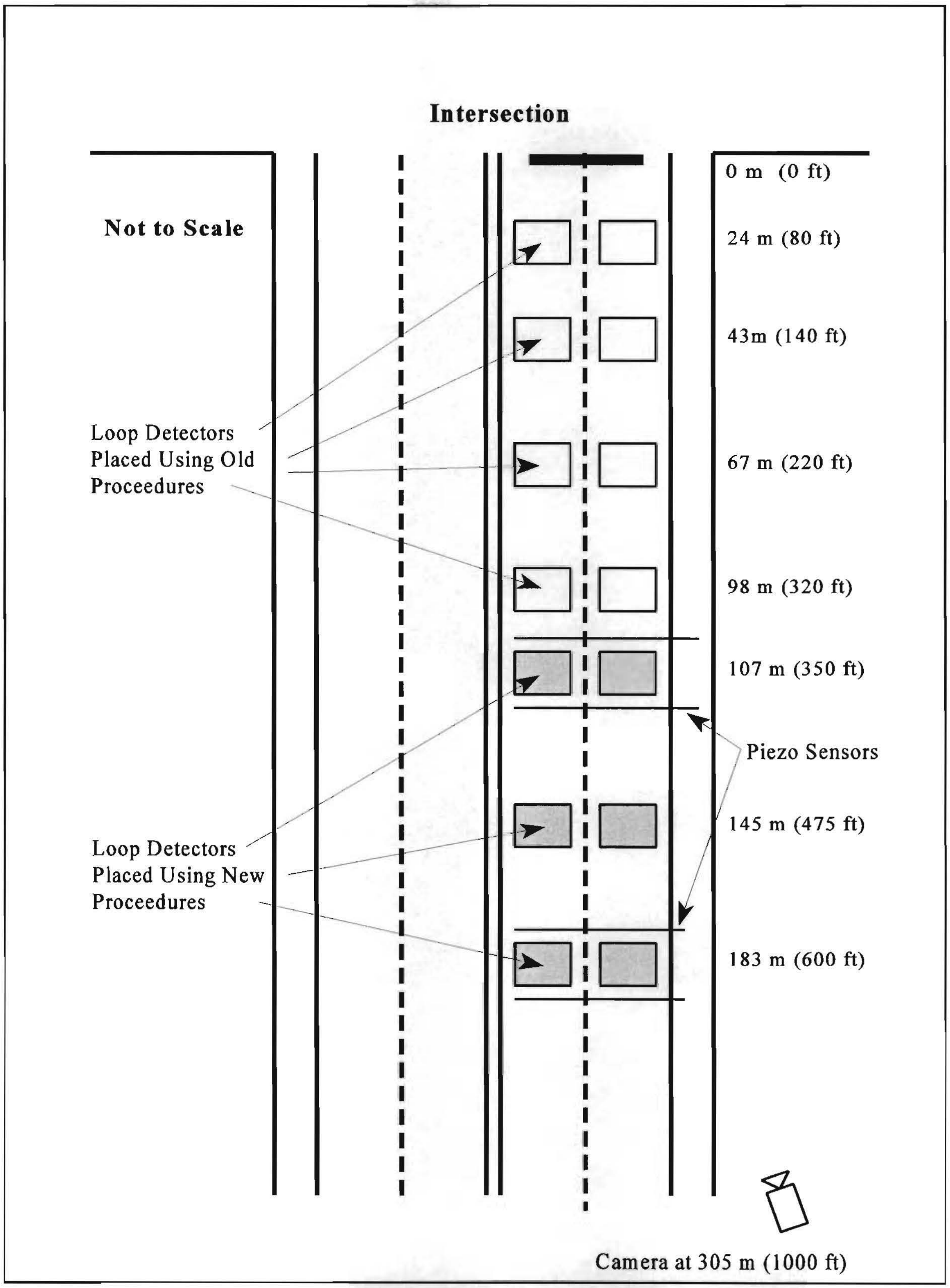

Figure 2-3. Location of Testing Equipment at Typical Signalized Intersection.

2.2.2 Data Collection Sites

A total of five sites were selected for analysis. Four of these sites were used for data collection, while one site was used to evaluate the test procedures used during the data collection. The sites used for this research were:

- FM 158 at FM 30/Elmo Weedon Road, Bryan, Texas
- US 290 at Mason Road, Houston, Texas
- SH 105 at Walden Road, Conroe, Texas
- SH 105 at April Sound, Conroe, Texas
- Business IH-20 at County Road 1290, Odessa, Texas

The new TxDOT procedures for ILD placement on high speed approaches require a change in the green extension time for the high speed approach. Table 2-2 presents the signal timings for the approach under analysis for the four sites used for data collection. The new green extension time of 1.2 seconds generally allows vehicles traveling greater than 97 km/h (60 mph) to continue past each successive detector and reach the end of the dilemma zone before the signal changes to yellow.

Table 2-2. Signal Timing Information for Approach Under Analysis.

Location	Min. Green (sec.)	Max. Green (sec.)	Existing Green Extension (sec.)	New TxDOT Green Extension for 113 km/h (70 mph) (sec.)
US 290 at Mason Road	25	80	2.0	1.2
SH 105 at Walden Road	20	60	1.0	1.2
SH 105 at April Sound	20	60	1.0	1.2
Business IH-20 at County Road 1290	25	60	1.0	1.2

Researchers selected the site due to the high approach speeds on at least one of the approaches to the intersections. The site used to test the procedures had a posted speed limit of 89 km/h (55 mph). The other four data collection sites each had a posted speed limit of 113 km/h (70 mph) on the studied approach.

2.3 DATA REDUCTION

While collecting data in the field, technicians marked various points along the approach to the intersection with orange traffic cones. Each point marked a particular distance from the stop bar at the intersection. These points were used to estimate a vehicle's distance from the intersection at the onset of the yellow phase. Based on Bonneson's study (*3*), the dilemma zone for a 113 km/h (70 mph) approach speed ranges from 76 to 183 m (250 to 600 ft) from the stop bar at the intersection; therefore, researchers marked the following distances: 76, 91, 122, 152, and 183 m (250, 300, 400, 500 and 600 ft).

Data reduction efforts began by locating the points on the videotape that were marked with orange traffic cones. Technicians marked each distance location on a clear sheet of plastic that covered the video monitor. Additional reference points, such as signs or poles, were also marked so technicians could determine whether the camera had moved during filming efforts.

During each yellow phase, technicians recorded the following: time that the yellow phase began, green time preceding yellow phase, approximate location of each vehicle in the dilemma zone at the onset of yellow, and the action that each driver in the dilemma zone made. Table 2-3 lists the categories used to describe the actions of drivers in the dilemma zone. Vehicles outside of the dilemma zone that ran a red light were also recorded. The reduced data were separated into passenger cars and trucks. Trucks included vehicles with three or more axles.

Table 2-3. Driver Actions During Yellow Phase.

Category	Driver Action
1	Stop
2	Run Yellow Light
3	Run Red Light
4	Brake Before Passing Through Intersection
5	Swerve To Avoid Collision
6	Abrupt Stop

From the six driver actions listed in Table 2-3, Actions 1 and 2 (stopped and run yellow light) are the most desirable and result in the least number of crashes. Actions 3 and 6 (run red light and abrupt stop) result in the most crashes and are to be avoided. Action 5 (swerve to avoid collision) is typically a result of another driver stopping abruptly. Action 4 (brake before passing through intersection) is a sign that the driver was located in the dilemma zone at the onset of yellow.

Data were typically collected over a four day period at each site (two days with the old loop configuration and two days with the new loop configuration). For each site, the goal was to reduce six hours of data for each loop configuration. In most situations, this was accomplished by reducing three hours of data for each day that data were collected. The three hours included one hour of data for each of the following three conditions: off-peak, peak, and night. For some days, however, it was not possible to obtain data for each of the three conditions because of various problems (such as video that was difficult to view or roadway maintenance that was performed by TxDOT during data collection). In these situations, the data were either collected during another day (if possible) or were not obtained. Table 2-4 provides a summary of the data that were reduced at each of the field sites.

2.4 DATA ANALYSIS

The goal of the data analysis was to compare the two types of loop configurations (old and new) for various traffic conditions. The data analysis was divided into the following three areas: approach speed, driver action, and vehicle location. Researchers used the speed data collected in the field to investigate the approach speeds of vehicles at each site. Driver action and vehicle location at the onset of yellow were derived from the video reduction efforts. Separate analyses were performed for passenger cars and trucks. Below are descriptions of the methodologies used for each study.

2.4.1 Approach Speed

Technicians collected speed data in the field using IRD classifiers that were capable of measuring individual vehicle speeds for each lane. Large samples of speed data measured at a location 183 m (600 ft) prior to the stop bar (at the beginning of the dilemma zone) were used to estimate the mean and 85^{th} percentile approach speeds. The samples of data included speeds during the peak, off-peak, and nighttime conditions. To estimate free-flow speeds approaching the intersection and remove the effects of the signal on traffic speed, all speeds of 72 km/h (45 mph) or less were removed from the sample. Because the speed limit at all study sites was 113 km/h (70 mph), the researchers assumed that all vehicles traveling at 72 km/h (45 mph) or less were either turning at the intersection or stopping for the red light.

2.4.2 Driver Action

As discussed in the *Data Reduction* section, the actions of drivers were recorded for each vehicle caught in the dilemma zone at the onset of yellow (see Table 2-3). After the data were reduced, researchers discovered that very few drivers performed actions 4 (brake before passing through intersection), 5 (swerve to avoid a collision), or 6 (skid during stop). Therefore, actions 4 through 6 were removed from the database and classified as either a 1 (stop), 2 (run yellow light), or 3 (run red light). This modification resulted in a more robust sample size for the statistical analysis.

Table 2-4. Summary of Data Reduction.

Site	City	Location	Date	Time	Loop Configuration	Condition
1	Houston	US 290@Mason	6/3/97	2:00-3:00 pm	Old	Off-Peak
				5:00-6:00 pm	Old	Peak
				9:00-10:00 pm	Old	Night
			6/4/97	5:00-6:00 pm	Old	Peak
				8:00-9:00 pm	Old	Night
			6/5/97	2:00-3:00 pm	New	Off-Peak
				4:00-5:00 pm	New	Peak
				8:00-9:00 pm	New	Night
			6/6/97	2:00-3:00 pm	New	Off-Peak
				5:00-6:00 pm	New	Peak
				8:00-9:00 pm	New	Night
2	Conroe	SH 105@Walden	6/10/97	7:05-8:05 am	Old	Peak
				2:00-3:00 pm	Old	Off-Peak
				8:30-9:30 pm	Old	Night
			6/11/97	7:00-8:00 am	Old	Peak
				10:00-11:00 am	Old	Off-Peak
				8:30-9:30 pm	Old	Night
			6/12/97	7:00-8:00 am	New	Peak
				1:00-2:00 pm	New	Off-Peak
				8:30-9:30 pm	New	Night
				9:30-10:30	New	Night
			6/13/97	7:00-8:00 am	New	Peak
				1:00-2:00 pm	New	Off-Peak
3	Conroe	SH 105@April Sound	6/16/97	8:30-9:30 pm	Old	Night
			6/17/97	7:05-8:05 am	Old	Peak
				10:00-11:00 am	Old	Off-Peak
				4:00-5:00 pm	Old	Peak
				8:30-9:30 pm	Old	Night
			6/18/97	1:15-2:15 pm	New	Off-Peak
				8:30-9:30 pm	New	Night
			6/19/97	7:00-8:00 am	New	Peak
				10:00-11:00 am	New	Off-Peak
				8:30-9:30 pm	New	Night
4	Odessa	Business IH 20 @ CR 1290	6/23/97	2:00-3:00 pm	Old	Off-Peak
				5:00-6:00 pm	Old	Peak
				9:00-10:00 pm	Old	Night
			6/24/97	7:35-8:35 am	New	Peak
				10:00-11:00am	New	Off-Peak
				9:00-10:00 pm	New	Night
			6/25/97	7:00-8:00 am	Old	Peak
				10:00-11:00am	Old	Off-Peak
				9:00-10:00 pm	Old	Night
			6/26/97	7:35-8:35 am	New	Peak
				10:00-11:00am	New	Off-Peak
				9:00-10:00 pm	New	Night

Before performing a statistical analysis, researchers combined the data reduced from the video for each site to generate the following data sets for both the new loop and old loop configurations: daytime and nighttime. The daytime data set included both peak and off-peak conditions. A total of four data sets were generated for each site (see Table 2-5). In addition, passenger cars were analyzed separately from trucks.

Table 2-5. Data Sets Generated for Each Site.

Data Set	Condition	Loop Configuration
1	Day	Old
2	Day	New
3	Night	Old
4	Night	New

Researchers conducted statistical analyses on the data sets to determine how each loop configuration performed under different circumstances. Separate analyses were performed for day and night conditions. Analyses included comparing the percentage of vehicles in the dilemma zone and the action of drivers in the dilemma zone at the onset of yellow for each loop configuration. Researchers performed statistical analyses using a 90 percent confidence level.

2.4.3 Vehicle Distance From Stop Line

While reducing the data, technicians approximated the distance from the stop line of each vehicle in the dilemma zone at the onset of yellow. This information was used to compare the locations of vehicles at the onset of yellow for the old and new loop configurations. In addition, the mean vehicle locations for the various driver actions (i.e., stop, run yellow, and run red) were computed and compared for the two loop configurations.

2.4.4 Loop Configuration Evaluation

One indicator of loop configuration performance is the maximum allowable headway (MAH). The MAH represents the maximum time headway that can occur between successive vehicle actuations before the phase in service gaps out. There is no set MAH that is best for all loop configurations. In general, shorter MAH's reduce the frequency of max-out and delay to waiting traffic; however, MAH's that are too short result in premature gap-outs. Bonneson and McCoy state that MAH's that are found to be effective range from 3 to 6 seconds *(12)*.

The *Manual of Traffic Detector Design (12)* provides a procedure for determining the MAH for a particular loop configuration and signal timing. It also provides methods for estimating the probability for max-out and average delay to vehicles on the cross street. The procedures in this manual were used to evaluate the old and new loop configurations for a 113 km/h (70 mph) approach speed.

2.5 SUMMARY OF RESULTS

2.5.1 Crash Analysis

The objective of the crash analysis was to compare crash data before and after the new loop configuration had been installed. To obtain crash data, the researchers interviewed DPS personnel and used TxDOT's accident database, LANSER. Because the new loop configuration was only temporarily installed as part of this project at Sites 1, 2, and 3, a before/after crash study could not be performed for these sites.

The researchers attempted to obtain before and after crash data for Site 4 (in Odessa at the intersection of Business IH 20 and County Road 1290). The new loop configuration at this site had been installed in May 1997; therefore, the researchers were hopeful that before and after crash data would be available. After researchers made an attempt to retrieve the crash data for this intersection, however, they discovered that the most current crash data were only available through February 1997.

In a further attempt to collect crash data at an existing field site, an additional site was chosen that was not part of the field study. This site was located in Brownwood at the intersection of US 377 and Crockett. The speed limit at this intersection was 80 km/h (50 mph). After an investigation of this site, however, researchers discovered that the new loop configuration was part of a new signal installation. Therefore, no before data were available at this site.

2.5.2 Field Studies

The data analysis for the field studies included investigating approach speeds to the intersection, driver actions in response to a yellow indication, and vehicle location at the onset of yellow. For the results on driver action and vehicle location, separate analyses were performed for passenger cars and trucks. Following is a summary of the results from the data analysis.

2.5.2.1 Approach Speed

- The 85^{th} percentile speeds for the field sites were below the 113 km/h (70 mph) posted speeds, ranging from 103 to 105 km/h (64 to 65 mph).
- Although the new detector configuration for a 113 km/h (70 mph) approach speed was designed to allow vehicles traveling faster than 97 km/h (60 mph) to exit the dilemma zone before the onset of yellow, 65 to 73 percent of vehicles at the study sites were traveling at

speeds slower than 97 km/h (60 mph), possibly resulting in being caught in the dilemma zone.

2.5.2.2 Driver Action

Passenger Cars

- The old loop configuration typically resulted in a higher percentage of passenger cars in the dilemma zone when compared to the new loop configuration.
- In a majority of the cases, the new loop configuration resulted in fewer passenger cars stopping at the intersection, more passenger cars running the yellow light, and fewer passenger cars running the red light when compared to the old loop configuration.
- For both old and new loop configurations, a small percentage of drivers (less than one percent of the total volume) that were located upstream of the dilemma zone (greater than 183 m [600 ft] from the intersection) at the onset of yellow ran the red light.

Trucks

- The new loop configuration resulted in more trucks stopping at the intersection, fewer trucks running the yellow light, and fewer trucks running the red light when compared to the old loop configuration.

2.5.2.3 Vehicle Distance From Stop Line

Passenger Cars

- The majority of passenger cars for the new loop configuration were located between 91 and 152 m (300 and 500 ft) from the stop line at the onset of yellow.
- For the old loop configuration, a higher percentage of passenger cars in the dilemma zone were not detected, resulting in a higher percentage of passenger cars being located further from the intersection at the onset of yellow when compared to the new loop configuration.
- For distances less than 118 m (390 ft) from the stop line, the majority of vehicles passed through the intersection at the onset of yellow; above this distance, the majority of vehicles stopped at the intersection.
- Ninety percent of all vehicles in the dilemma zone stopped at the intersection when presented with a yellow indication at a location approximately 175 m (575 ft) from the stop line. In addition, 90 percent of all vehicles pass through the intersection at the onset of yellow at a location approximately 80 m (260 ft) from the stop line.

Trucks

- Similar to the results for passenger cars, a higher percentage of trucks were located farther upstream of the stop line at the onset of yellow for the old loop configuration when compared to the new loop configuration.
- For distances less than 128 m (420 ft) from the stop line, the majority of vehicles passed through the intersection at the onset of yellow; above this distance, the majority of vehicles stopped at the intersection.
- Ninety percent of all vehicles in the dilemma zone stopped at the intersection when presented with a yellow indication at a location approximately 170 m (560 ft) from the stopline. In addition, 90 percent of all vehicles pass through the intersection at the onset of yellow at a location approximately 75 m (250 ft) from the stop line.

2.5.2.4 Loop Configuration Evaluation

- The max-out probability for both old and new loop configurations was zero for flow rates below 1000 vph. For flow rates above 1000 vph, the max-out probability began to significantly increase for both loop configurations.
- The difference in max-out probability between the old and new loop configurations was relatively small.
- The average delay to cross street traffic was similar for both the old and new loop configurations.

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

The results from the field study revealed that the new loop configuration is as good as, and in some cases better than, the old loop configuration. Because the new loop configuration can detect vehicles further upstream from the intersection (at the beginning of the dilemma zone), it results in fewer vehicles being caught in the dilemma zone at the onset of yellow. Also, because the new loop configuration typically resulted in more vehicles running the yellow light instead of stopping, fewer rear-end crashes may result. In addition, the new loop configuration resulted in fewer vehicles running the red light, also a major cause of crashes. The proposed detector spacing and green extension values for these speeds are as shown in Figure 3-1.

3.2 RECOMMENDATIONS

3.2.1 Implementation

TxDOT's new procedures for detector placement address all high-speed approaches from 72 km/h (45 mph) to 113 km/h (70 mph). The results of this research indicate that the new TxDOT detector placement performs as expected in detection of vehicles at much greater distances from the intersection. This provides more distance (or time) to make the appropriate decision upon the onset of yellow, then red. The new detector placement plan has already been implemented in a few districts where 113 km/h (70 mph) approaches exist. With the successful outcome of this project, this detector scheme should be implemented elsewhere at intersections which are otherwise safe for these speeds. Based on the findings from this study, it is recommended that the detector layout be based on the 85th percentile approach speed to the intersection (as opposed to the posted speed limit). Deliverables for this project include a standard sheet for implementation of the new detector layout on future construction projects.

3.2.2 Future Research

Even though the new TxDOT procedures provide detection substantially farther away from the stop line than the old procedures, there are still uncertainties regarding effectiveness of vehicle detection systems at high-speed signalized intersections. Two of the areas that need further research include detection by lane and by vehicle type. In many cases, for example, ILDs on multilane approaches do not distinguish detections in lane one from lane two. Vehicle type is important from the standpoint of different operating characteristics between cars and other smaller vehicles, and trucks. An enhanced system that has the capability of detecting vehicle types and speeds could utilize inductive loops and the new series of Advanced Traffic Controllers that are already becoming available.

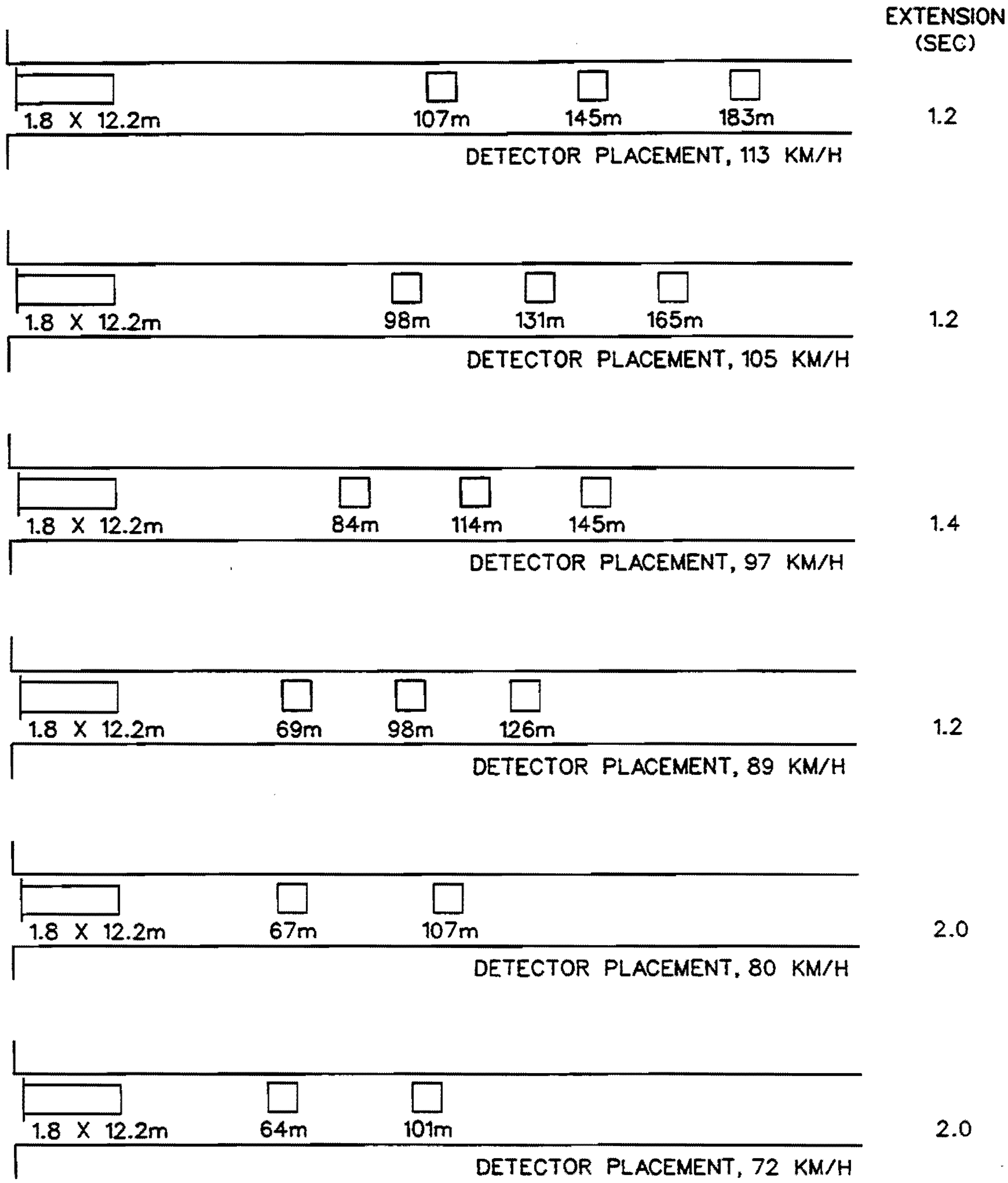

Figure 3-1. Proposed Detector Placement

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