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16. Abstract

Early indications from the use of the newest vehicle detectors for high-speed signalized intersections suggested that they perform well as replacements for the Texas Department of Transportation's (TxDOT's) legacy systems, but this early conclusion needed verification based on rigorous field testing in a variety of traffic and environmental conditions. This research investigated the performance characteristics of detectors designed for the stop line area and indecision zone detection. In some cases, new detectors involved two technologies to cover both upstream and stop line areas. Increasing use of infrared (IR) cameras with video imaging systems was an attempt to overcome some of the limitations of traditional video detection. While these IR cameras may improve video detection for some lighting and temperature conditions, evidence suggested that they do not improve detection performance under all conditions.

The objectives of this research were to:

- Determine current TxDOT-specific needs for new vehicle detectors.
- Identify the most promising detectors for both stop line and dilemma zone detection.
- Develop guidelines on each new technology and establish recommended controller and detector settings to guide TxDOT on installation and use of each detector and combination of detectors.

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DISCLAIMER

The contents of this report reflect the views of the authors, who are solely responsible for the facts and accuracy of the data, the opinions, and the conclusions presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT), Federal Highway Administration (FHWA), The Texas A&M University System, or the Texas A&M Transportation Institute (TTI). This report does not constitute a standard or regulation, and its contents are not intended for construction, bidding, or permit purposes. The use of names or specific products or manufacturers listed herein does not imply endorsement of those products or manufacturers. The engineer in charge of the project was Dan Middleton, P.E. #60764.

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EXECUTIVE SUMMARY

INTRODUCTION

This research investigated the performance characteristics of new or untested detectors designed for the stop line area and indecision zone detection upstream of high-speed signalized intersections. The objectives of this research were to:

- Determine current TxDOT-specific needs for new vehicle detectors.
- Identify the most promising detectors for both stop line and dilemma zone detection.
- Develop guidelines to assist TxDOT on installation and use of each detector and combination of detectors.

DATA COLLECTION PLAN

In the first task, the research team proposed a list of detectors, general locations for tests, and the methodology of testing for consideration by TxDOT for this research project. As part of the Test Plan, the research team proposed what to test, where to test, and test metrics for collecting and analyzing data. This plan, once approved by the Project Monitoring Committee (PMC), provided the basic foundation for the remainder of the project. Table ES-1 lists the detectors included in this research project. Testing began at the Texas A&M University Riverside campus and concluded at four selected TxDOT intersections.

Table ES-1. Desired Detector Tests.

Detection System	Test Upstream	Test at Stop Line
1.Aldis GridSmart	Vehicle detected: yes/no When detection begins When detection ends	Vehicle detected: yes/no Stop line call starts Stop line call ends
2. FLIR VIP w/IR camera	Vehicle detected: yes/no When detection begins When detection ends Compare against optical camera	Vehicle detected: yes/no Stop line call starts Stop line call ends
3. Iteris Vantage Vector	Vehicle detected: yes/no Tripwire detection TL1, TL2, TL3 Tripwire detection TL1, TL2, TL3 DZ prediction accuracy	Vehicle detected: yes/no Stop line call starts Stop line call ends
4. Trafficware Pods	Vehicle detected: yes/no Where detection begins Where detection ends	Vehicle detected: yes/no Stop line call starts Stop line call ends
5. Wavetronix SS Advance (SS-200E)	Vehicle detected: yes/no Where detection begins Where detection ends Tracking accuracy (position) DZ prediction accuracy Vehicle class (truck/non-truck)	N/A
6. Wavetronix SS Matrix	N/A	Vehicle detected: yes/no Stop line call starts Stop line call ends

FIELD DATA FINDINGS

Riverside

Based on the controlled environment at the Riverside campus and a very simple test scenario of constant speed and a single vehicle in the detection zone at a time, only one of the originally selected detectors was determined unready for further tests. Table ES-2 summarizes results from the Riverside tests for remaining detectors in terms of detector presence times. For these data, each vehicle passage should produce one "on" and one "off" detector event for each detector. If a run did not register a detection event, the result was considered a missed call. False calls happen when a single run registers more than one on or one off event. Detection rates are calculated as the ratios of the number of detection events to the number of runs. Results less than 100 percent imply missed calls, false calls, and/or stuck-on calls.

Table ES-2. Correct Riverside Detection Rates. [a]

Detector	50 mph				70 mph			
	Day, Dry	**Trans, Dry**	**Night, Dry**	**Day. Rain**	**Day, Dry**	**Trans, Dry**	**Night, Dry**	**Day, Rain**
FLIR VIP Stop Line [b]	94.01%	95.74%	98.14%	97.67%	97.39%		99.44%	95.65%
Iteris Stop Line [b]	93.83%	100.00%		71.43%	78.79%	100.00%		0.00%
Iteris Trip at 485 ft	79.01%	93.33%		95.24%	87.88%	72.73%		56.41%
Iteris Trip at 566 ft					39.39%	72.73%		48.72%
Wavetronix Matrix [b]	101.30%		97.56%	106.90%	97.92%			90.00%
Wavetronix Advance	94.81%		97.56%	96.55%	97.92%			96.67%
Aldis Upstream	75.46%	67.77%	98.90%	85.78%	6.55%	0.00%	100.00%	0.00%
Aldis Stop Line [b]	79.60%	87.60%	98.14%	100.43%	92.09%	100.00%	100.00%	100.00%
Pod at stop line	92.81%	96.69%	97.67%	91.81%	98.98%	100.00%	98.89%	98.55%

[a] Shaded cells indicate no data for that condition.

[b] Stop line detections consider stuck-on and dropped calls as correct detections.

TxDOT Intersections

Four intersections, two in the Austin District and two in the Houston District, produced the results shown in Table ES-3. Due to several limitations in Project 0-6828, these observations should be supplemented in more extensive future data collection efforts.

Table ES-3. Intersection Findings.

Detector	Location	Stop Line	Upstream
Aldis GridSmart	Houston	Correct 61.3% to 90.6%	N/A
FLIR VIP w/IR cam	Houston	Correct 99.6% Night	Correct 73.1% to 81.0% Day
Iteris Vantage Vector	Austin	N/A	Correct 71.4%
Trafficware Pods	Austin	Correct 97.1%	Correct 92.9%
Wavetronix Advance	Austin	N/A	Excellent controller ext. for trucks
Wavetronix Matrix	Austin	Correct 91.4% to 99.6%	N/A

GUIDELINES FOR NEW DETECTORS

Tables ES-4 and ES-5 provide a quick reference for users.

Table ES-4. Quick Reference for Stop Line Detectors.

Detection System	Strengths	Weaknesses
1.Aldis GridSmart	• Single camera for all approaches • Single CAT5 cable to camera • Convenient video recording • Optional turning movement counts	• Camera location is critical • Video is subject to weather/light conditions • Camera maintenance
2. FLIR VIP w/IR camera	• Nighttime and some inclement weather detection improved	• Higher cost of IR camera • IR video is still subject to some light and weather conditions
3. Iteris Vantage Vector	• Lower cost than some options • One installation point for two detectors	• Video is subject to some light and weather conditions
4. Trafficware Pods	• Quicker to install than loops • Cost competitive with loops • Presence detection excellent • Not affected by weather/light	• Intrusive requiring traffic control • Latency of presence on
5. Wavetronix SS Advance (SS-200E)	N/A	N/A
6. Wavetronix SS Matrix	• Radar immune to most weather • One detector covers 10 lanes	• Higher cost • High stuck-on call rate • High false calls during snowfall

Table ES-5. Quick Reference for Upstream Detectors.

Detection System	**Strengths**	**Weaknesses**
1.Aldis GridSmart	• Single CAT5 cable to camera • Convenient video recording	• High false call rate upstream • Camera maintenance
2. FLIR VIP w/IR camera	• Nighttime and some inclement weather detection improved	• Missed calls midday hot weather • Higher cost of IR camera
3. Iteris Vantage Vector	• Radar immune to most weather • Small footprint for 2 detectors	• May not be appropriate for highest speeds
4. Trafficware Pods	• Quicker to install than loops • Cost competitive with loops • Presence detection excellent • Not affected by weather/light	• Intrusive requiring traffic control • Detection latency but user can compensate
5. Wavetronix SS Advance (SS-200E)	• Patented Time of Arrival concept • Longest detection range for high speeds • Radar immune to most weather • Accurate dilemma zone detector	• Limited classification accuracy
6. Wavetronix SS Matrix	N/A	N/A

CHAPTER 1. INTRODUCTION

PURPOSE

Early indications from the use of the newest vehicle detectors for high-speed signalized intersections suggested that they perform well as replacements for the Texas Department of Transportation's (TxDOT's) legacy systems, but this early conclusion needed verification based on rigorous field testing in a variety of traffic and environmental conditions. This research investigated the performance characteristics of detectors designed for the stop line area and indecision zone detection. In some cases, new detectors involved two technologies to cover both upstream and stop line areas. Increasing use of infrared (IR) cameras with video imaging systems was an attempt to overcome some of the limitations of traditional video detection. While these IR cameras may improve video detection for some lighting and temperature conditions, evidence suggested that they do not improve detection performance under all conditions.

BACKGROUND

The traditional detection method that has been used by TxDOT on high-speed signalized intersection approaches for many years involved multiple detection points with inductive loops being the early favorite in terms of technology. However, TxDOT districts began adopting video imaging systems to replace loops as video began to show sufficient improvement, even though they were not as accurate as loops. This video trend continued to the point that the usage of video surpassed the usage of loops. However, the subsequent availability of other technologies at a reasonable cost caused TxDOT to seriously consider replacing both loops and video with newer systems that were immune to weather and lighting issues. Most of the newer systems also overcame the challenge of traffic interference and weakening pavement that plagued loops.

OBJECTIVES

The objectives of this research were to:

- Determine current TxDOT-specific needs for new vehicle detectors.
- Identify the most promising detectors for both stop line and dilemma zone detection.
- Develop guidelines on each new technology and establish recommended settings to guide TxDOT on installation and use of each detector and combination of detectors.

REVISIONS TO WORK PLAN

In *Task 1 Develop Test Plan*, the research team proposed a list of detectors, general locations for tests, and the methodology of testing for consideration by TxDOT for this research project. The plan involved high-speed tests first in the controlled environment of the Texas A&M University (TAMU) Riverside campus followed by installation and testing of selected detectors at TxDOT signalized intersections. The research team installed detectors at Riverside as soon as the detectors became available and completed their installation in January 2015.

Given the fact that most of the detectors selected for inclusion in this research were either new or relatively new and not well known, several discoveries in the early testing required modifications to the work plan. Two of the issues that required a change to the methodology involved radar detectors either for upstream detection or stop line detection. The initial issue involved operating multiple radar detectors simultaneously in close proximity to each other, resulting in possible interference. The research team could not determine conclusively based on resulting data nor could the consulted experts determine whether interference would occur for sure. Therefore, testing beyond that point in time occurred with only one system running at a time with the exception of the two detectors from Wavetronix, which were designed to be operated together.

The other radar issue involved one of the newest radar detectors using a process similar to an existing radar detector whose process was patented. Both of these detectors were included in the project. As testing progressed at Riverside, the manufacturer of the newer detector had to stop manufacturing its product with the conflicting firmware. Fortunately, that manufacturer had built in a secondary method to replace its primary method. All of the data that the research team had collected to that point would not apply to the alternate procedure, so researchers had to start over for that detector.

Another change in the work plan during the Riverside tests resulted from difficulties with one of the hybrid detectors selected in the data collection plan. Several challenges in early attempts to make it detect properly indicated that its continued testing in this project was premature. The research team worked with the manufacturer through both hardware and firmware changes to achieve proper performance, but the effort became more than could be sustained and meet project goals.

ORGANIZATION OF THE REPORT

This research report consists of six chapters organized by topic. Chapter 2 provides the results of a thorough literature review. Chapter 3 describes the efforts involved in conducting field data collection under controlled conditions at the Texas A&M University Riverside campus. Chapter 4 follows the controlled tests with intersection tests at four intersections in the TxDOT Austin and Houston Districts. Chapter 5 presents results and analysis of the field data as a prelude to developing the Guidelines for New Vehicle Detectors in Chapter 6. A component of the Guidelines is a Quick Reference Guide on strengths/weaknesses of various detectors included in this research.

CHAPTER 2. LITERATURE REVIEW

INTRODUCTION

Detection design at signalized intersections consists of two topics: detector layout and detection-related control settings (*1*). Detector layout consists of locating and configuring the needed detection zones to provide stop-line detection and advance detection for indecision zone protection on high-speed approaches. Detection-related control settings consist of detection mode (presence or pulse), passage time, and extend. TxDOT's *Traffic Signal Operations Handbook* (referred to hereinafter as the *Handbook*) provides guidelines for these topics for both stop-line and advance detection. The *Handbook* provides guidelines for using inductive loops for high-speed advance detection applications but states that video detection is not recommended for such applications because detection accuracy degrades with distance. This performance degradation can take the form of missed calls when rapidly-approaching vehicles pass through the advance detection zones and can lead to green signal indications being terminated when drivers are in their dilemma zone.

Due to cost and maintenance issues, TxDOT districts have been increasing their use of video detection for years (*2, 3*). As of 2012, radar was the third-most common detection technology used by both TxDOT districts and Texas cities, behind video and inductive loops. Interviews with various agencies revealed that new inductive loop detectors are rarely installed, and inductive loop systems in place represent existing legacy systems that are being replaced with other technologies as they fail. Interviewees generally stated that they choose detection technologies based on the need to provide adequate detection while minimizing installation cost and the need to install new cabling or hardware in the controller cabinet (*3*).

As a preview to the extensive search related to developing a short list of detectors for inclusion in field tests, this document looks at the "dilemma zone" or "indecision zone." While some researchers prefer the term indecision zone over the dilemma zone, this document does not differentiate between the two and both terms are used interchangeably.

DILEMMA ZONES

This section provides an overview of dilemma zone concepts and vehicle detection systems designed to mitigate the risk from dilemma zones. Other vehicle detection systems and algorithms designed to improve operational efficiency at signalized intersections are also discussed.

Definitions of Dilemma Zones

The dilemma zone or the indecision zone is the portion of the intersection approach within which drivers exhibit distinct differences or abilities to stop at the onset of the yellow indication (*4*). Figure 1 shows the typical location of the dilemma zone.

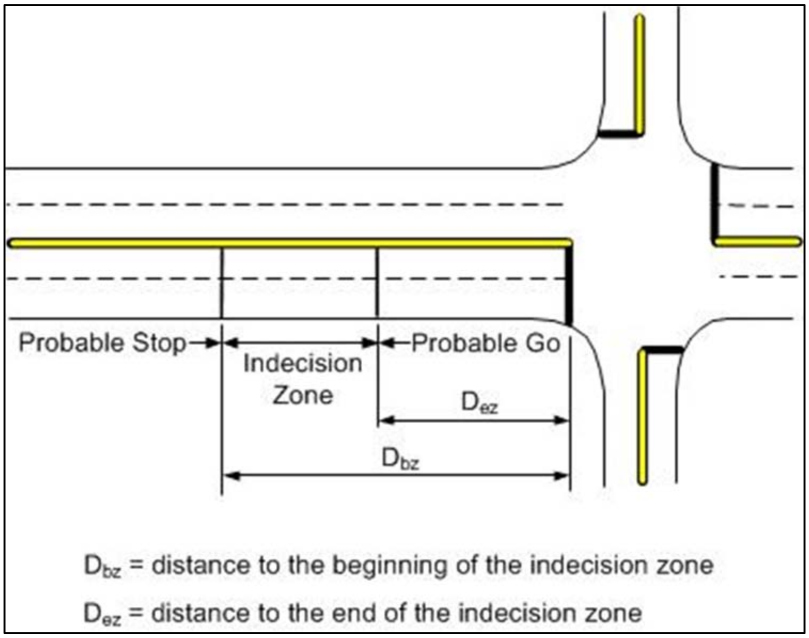


Figure 1. A Dilemma Zone on a Typical Intersection Approach (*1*).

There are two major approaches to defining dilemma zone boundaries (*5*).The first approach defines the dilemma zone based on the law of physics and vehicle kinematic properties. This type of dilemma zone is also known as Type I dilemma zone. As defined in Gazis et al. (*6*), the stopping distance needed by a vehicle to stop at the onset of yellow indication can be computed as:

$$X_s = Vt_R + \frac{V^2}{2a_1} \qquad (1)$$

Where

X_s = Stopping distance to stop bar (*ft*).
V = Vehicle speed (*ft/s*).
t_R = Perception-reaction time (*s*).
a_1 = Maximum deceleration rate (*ft/s*^{2}).

The traveling distance required for a vehicle to clear an intersection can be computed as:

$$X_c = Vt_R + \frac{1}{2}a_2(Y - t_R)^2 - (w + L) \qquad (2)$$

Where

X_c = Traveling distance to a stop bar (*ft*).
w = Intersection width (*ft*).
L = Vehicle length (*ft*).
Y = Yellow interval (*s*).
a_2 = Maximum acceleration rate (*s*).

A dilemma zone exists when a vehicle is in a position where it can neither stop nor clear the intersection safely, i.e., when $X_s > X_c$ and the vehicle is located within this boundary. When $X_c > X_s$, drivers between X_c and X_s can choose either option and therefore are in what is sometimes referred to as the option zone (*7*).

In the second approach, researchers characterize the dilemma zone based on the drivers' probabilistic nature in their decisions whether to stop or to proceed at the onset of yellow indication. These are also referred to as Type II dilemma zones, indecision zones, and option zones. The Type II dilemma zone boundary can be defined either in terms of distance or travel time to the stop bar. Zegeer (*8*) defined the beginning of the zone as the distance beyond which 90 percent of all drivers would stop if presented with a yellow indication and the end of the zone as the distance within which only 10 percent of all drivers would stop. This range is equivalent to the travel time to the stop bar of 4.5–5.0 s to 2.0–2.5 s (*9*). Bonneson et al. (*10*) suggested that the beginning of the dilemma zone is 5.0–6.0 s upstream, and the end is about 3.0 s upstream. Figure 2 provides a comparison of dilemma boundaries as defined by the observed distance, observed travel time, and safe stopping distance criteria.

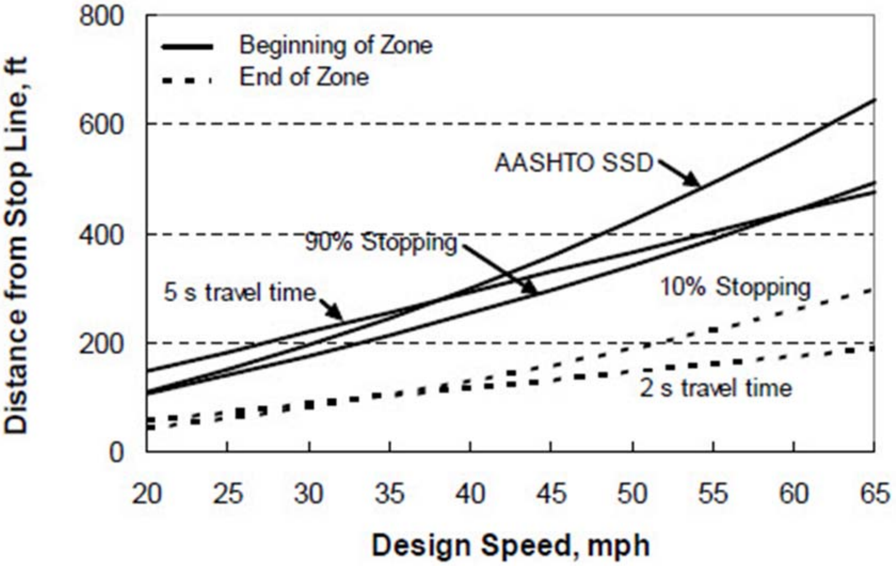


Figure 2. Comparison of Dilemma Zone Boundaries (*11*).

Drivers also behave differently when they are in the dilemma zones. Gates and Noyce (*12*) examined various aspects of driver behavior at 2.0 to 6.5 sec upstream of the stop bar at the onset of yellow indication at six urban or suburban signalized intersections in Wisconsin. The time interval used in the study was slightly larger than typical ranges reported in the literature in order to capture all vehicle types. The data were collected using a video camera mounted on a 20-ft steel pole between 400 and 800 ft upstream of the intersection. The data were collected only during dry daylight hours. The approach speeds were calculated using the vehicle's time to traverse the initial 50 ft of the intersection approach. The average deceleration rate was computed by dividing the approach speed by the braking time. The braking time was computed as the time elapsed from when the brake lights became illuminated to when the vehicle had stopped. The vehicles were classified into one of five categories: motorcycle, car, light truck (pickup, SUV, van, minivan), single-unit truck (single-unit heavy truck, delivery truck, recreation vehicle, bus), and tractor trailer (multiunit heavy truck). Each observation was also classified by time of day and whether the vehicle was part of a platoon.

The researchers conducted the statistical analysis on the data sets using the analysis of variance (ANOVA). The study concluded the following:

- Vehicle type was found to have a statistically significant effect on both deceleration rate and red light running occurrence but not the brake response time.
- Deceleration rates were highest for cars and light trucks.
- Tractor trailers and single-unit trucks were 3.6 and 2.5 times more likely to commit red light running compared with passenger cars, respectively.
- Deceleration rates were significantly higher during off-peak hours.
- Red light running was 1.3 times more likely to occur during peak periods compared with off-peak periods.

Vehicle Detection Systems

A vehicle detection system monitors vehicles in its dilemma zone using detectors with the objective of preventing the phase termination when there are vehicles within its indecision zone.

Green-Extension Systems

Green-extension systems are the most commonly used operation at high-speed intersections in the United States. These systems use multiple advance detectors along each high-speed approach and standard controller functions to extend the green until both phases can end when there are no vehicles on either approach or when the maximum green is reached (*4*). If the phases gap out, the dilemma zone protection is provided for all vehicles. However, if the phases max out, the safety benefit is completely ignored. Therefore, this type of implementation is also considered an all-or-nothing approach.

The layout for such a system, based on 60 mph design speed, is shown in Figure 3. Some of the suggested layouts and settings for detection design are shown in Table 1, and more details can be found in the Traffic Signal Operation Handbook (*13*).

The operation for the stop line detector (if it exists) is in deactivated mode which means it is active only for initial queue discharge and disconnected after its first gap-out. This operation will guarantee the most efficiency by avoiding unnecessary green extension. In case of no stop bar detector, minimum recall must be set in the controller and the minimum green should be set appropriately for initial queue service.

Li et al. (*7*) proposed an alternative design for dilemma zone protection using a two-detector configuration. The design was based on the optimization objective to minimize the combined cost of safety and delay. The safety was quantified by the dilemma conflict potential which is derived from conflict probabilities of vehicles as a function of speed and locations of conflicting vehicles. The optimization trials were carried out using Vissim microscopic simulation. The results were evaluated only within the simulation environment and for design speeds from 40 to 55 mph. Li et al.'s proposed detection zone is narrower than those of Bonneson et al.'s configuration shown in Table 2.

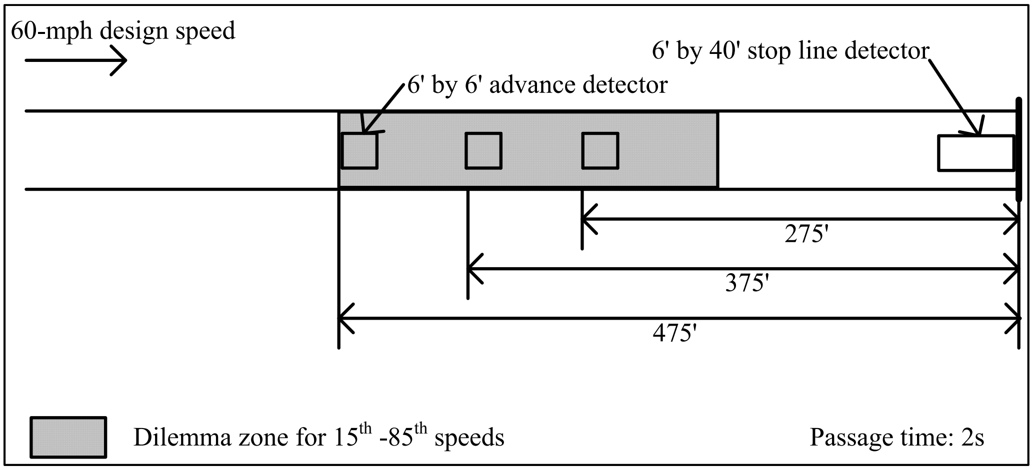


Figure 3. Multiple Advance Detector System (*13*).

Table 1. Layout and Settings for Multiple Advance Detector System (*13*).

85% Approach Speed (mph)	Distance to 1st Detector (ft)	Distance to 2nd Detector (ft)	Distance to 3rd Detector (ft)	Passage Time (s)
70	600	475	350	1.4-2.0
65	540	430	320	1.6-2.0
60	475	357	275	1.6-2.0
55	415	320	225	1.4-2.0
50	350	220	-	2.0
45	330	210	-	2.0

Table 2. Comparison of Detector Layout.

85% Approach Speed / Speed Limit (mph)	Bonneson et al. (*13*)		Li et al. (*7*)	
	Distance to 1st Detector (ft)	Distance to 2nd Detector (ft)	Distance to 1st Detector (ft)	Distance to 2nd Detector (ft)
55	415	320	413**	309**
50	350	220	349	274
45	330	210	310	236
40	*	*	255	209

* Not provided because the design is for high-speed approaches of 45 mph or higher.
** Bonneson et al.'s configuration uses three advance detectors for 55 mph and higher.

Sharma et al. (*14*) examined the current practice of using simultaneous gap-out logic in green-extension systems. In actuated control, phases 2 and 6 (major through phases) are often linked for gap-out purposes with the intent of providing safe phase termination. With the simultaneous gap-out constraint, these two phases must gap out simultaneously to cross the barrier. Hence, this logic inherently increases the likelihood of max-out under medium to high volume conditions. This study showed that safety benefits are negated under medium to high volume conditions where the major phases are arbitrarily maxed out. The simultaneous gap-out logic can lead to max-outs ranging from 3.5 percent to 40 percent of cycles per hour during the peak traffic flow period s and around 200 dilemma zone incursions per day.

There also exist enhanced versions of green-extension systems, including the TTI Truck Priority System and the Swedish LHOVRA system. The TTI Truck Priority system was designed specifically to reduce the number of trucks stopping on high-speed rural intersection approaches (*15*). The system includes a basic green extension system plus a detector speed trap for each lane and a vehicle classifier located at about 7.0 s upstream of the intersection to identify trucks. If the signal is green and a truck is identified, the computer directs the controller to hold the phase until the truck reaches the end of the clearance zone based on its measured speed.

The LHOVRA was initiated in 1979 by the Swedish National Road Administration to reduce crash frequency and delays at intersections on high-speed roads (*16*). The LHOVRA acronym stands for six system functions. The O-function is intended to provide dilemma zone protection while alleviating the limitations of simultaneous gap-out logic. The O-function works like basic green-extension system but allows for separate termination of the green for each major-road phase by separately monitoring the detectors on each approach. The first phase can terminate when it has already gapped out and there is no vehicle in the clearance zone the moment at which the second phase also gaps out or maxes out. If there is a vehicle in the clearance zone, the first phase is allowed to extend green until the clearance zone is clear or 12 s elapses.

Green-Termination Systems

The green-termination systems determine the best time to end a phase. The most notable systems are the intelligent Detection-Control System (D-CS) (*4*) and the Swedish Self Optimizing Signal (SOS) system (*17*). These systems are designed to identify an appropriate time to end the green phase by predicting the value of a performance function for the near future. This performance function is based on the number of vehicles in the dilemma zone and the opposing queue. The safety cost is calculated using the number of vehicles in the dilemma zone.

Sharma et al. (*9*) proposed an enhanced operation of green termination systems using a marginal cost-benefit approach to determine when to terminate the green. In this approach, the high-speed through phase is extended beyond the end of the saturation discharge rate until the cost experienced by the opposing movements exceeds the estimated safety benefits associated with extending the phase. The safety benefit is computed using a concept of Decision Conflict Zone (DCZ), which is defined as the region in which the driver must make a decision regarding conflicting options of stopping or proceeding through. The DCZ is represented by a hazard function (see Figure 4) where one could seek to minimize the area under this function during heavy traffic conditions instead of entirely eliminating it. The safety benefit is estimated by the cost of conflicts, which is based on the accident cost and the probability of an accident given a particular type of conflict.

The delay cost incurred from clearing a vehicle through its DCZ is estimated by the amount of delay incurred by the queue that formed on the stopped phases. The algorithm then seeks the break-even point to terminate the phase which is the point in time when the cost of allowing *n* vehicles on *m* approaches from their DCZ equals the increase in the system delay cost associated with clearing them through. While this marginal cost-benefit concept is appealing, it requires exact knowledge of vehicle positions from the stop bar. In addition, it has not been evaluated in the field.

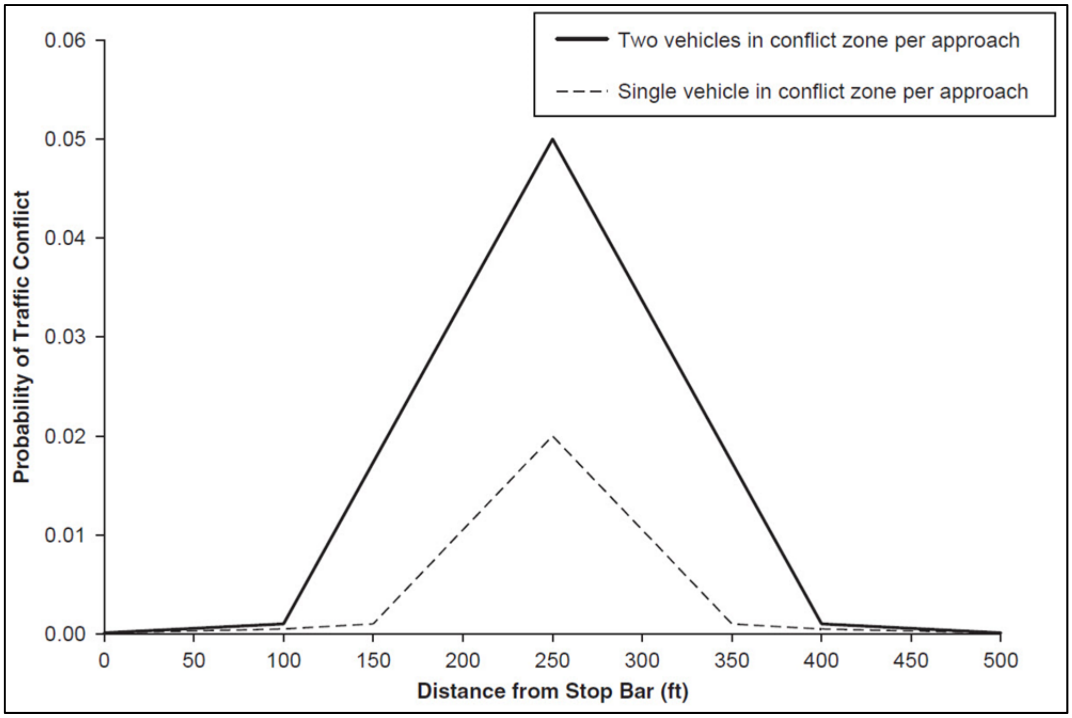


Figure 4. Hypothetical Hazard Function (*9*).

Detection Systems for Enhancing Operational Efficiency

Smaglik et al. (*18*) proposed a new tactical control algorithm that monitors the real-time stop bar presence detection and real-time flow rate information to identify a downstream bottleneck. If a flow restriction exists, the algorithm can terminate a phase with constant call earlier than its specified maximum or split time.

The detector setup used in this study is similar to those found at typical actuated intersections. The detector used for analysis is a 51-ft stop bar detector with two outputs, presence and count. Vehicle counting with stop bar detection is based on emerging technology that analyzes the inductive waveform of vehicles passing over a large presence detection zone, providing a short contact closure every time a vehicle is counted.

The algorithm identifies the bottleneck if the following conditions are all satisfied:

- Phase is green.
- Flow < Specified Threshold during the last *t* seconds.
- Presence = ON.

The algorithm then terminates the phase if the bottleneck is identified; otherwise, the green interval timing continues. The evaluation of the algorithm with the field data over a 504-hour period of signal operation showed that the algorithm could identify 76 bottlenecks with 75 percent of these events visually confirmed by the video review.

Evaluation of Advance-Detection Design

Pratt and Bonneson (*19*) described a framework for evaluating an advance-detection design. The framework accounts for the detection layout, traffic conditions, and controller settings. The framework is based on measures of control delay, probability of ending the green phase through max-out, and probability of providing indecision-zone protection during green-phase gap-out, which is referred to as "detection coverage." An effective detection design provides an optimal balance between safety and operations. For example, if a short passage time is used, the major phases are easier to terminate by gap-out, which results in shorter average cycle length and delay. However, it also increases the likelihood of vehicles trapped within the indecision zone. Long passage times similarly can increase delay and cause phase termination by max-out which also reduces safety.

Max-out probability represents the likelihood that the green interval will extend to its maximum limit. When the phase terminates in this manner, there is a possibility of vehicles on the intersection approach at the onset of yellow, and the resulting conflicts may lead to rear-end crashes.

Detection coverage is an indication of the extent to which the detection design will protect a vehicle when it is in its decision zone. The detection coverage is computed based on the probability of dilemma, which is shown in Figure 5. The probability of a dilemma is at its maximum when the probabilities of stopping and going are both equal to 0.5.

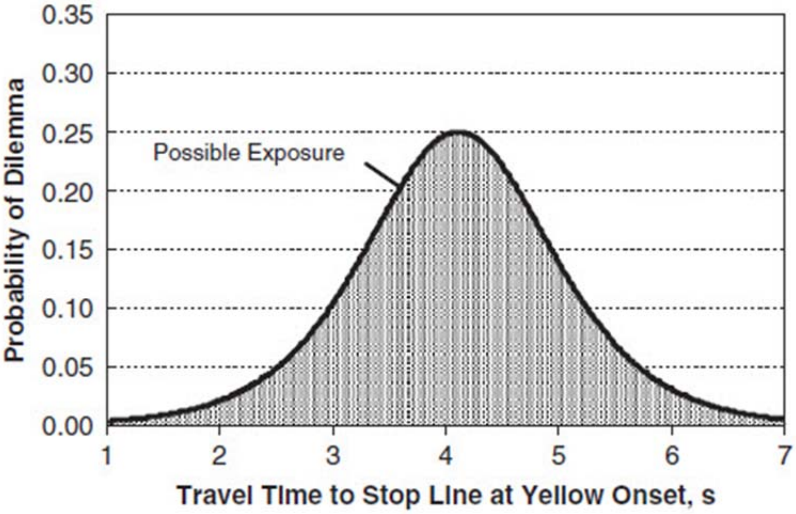


Figure 5. Probability of Dilemma (*19*).

For a given speed, vehicle calls at advance detectors will extend the passage time. Figure 6 illustrates the scenario in which the passage time is inadequate to carry the vehicle to the next detector before it expires. Thus, the yellow will be presented when the vehicle is still in its indecision zone. The summation of unshaded portions under the curve represents the detection coverage. Given that the phase is gapping out, the probability of indecision zone coverage is defined by:

$$P_{\text{cov|gap}} = \frac{\text{Detection Coverage}}{\text{Possible Exposure}} \tag{3}$$

For accurate quantification, the detection coverage is computed for the distribution of vehicle speeds and volumes and is reported as an overall average.

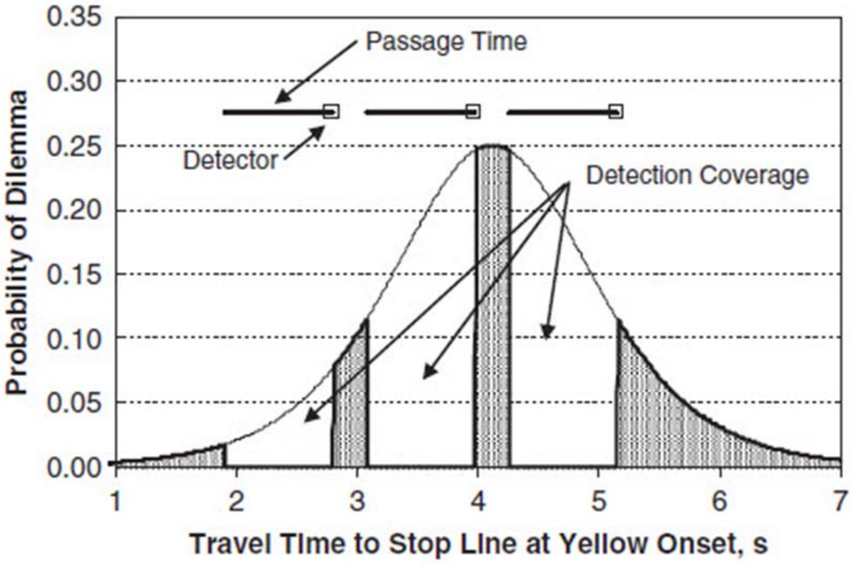


Figure 6. Concept of Detection Coverage (*19*).

To illustrate the application of the framework, the study analyzed the detection designs used in Texas as shown in Table 3. The analysis showed that the stop line detector operation has significant influence on coverage. The detection coverage is reduced to 80 percent or less if it is active throughout the green interval. In contrast, it can provide detection coverage of about 93 percent if the stop line detector is deactivated after gap-out.

Figure 7 shows how the framework can be applied to select the appropriate passage time for a given detection layout. For example, if the approach has a design speed of 60 mph and the stop line detector is deactivated after gap-out, the passage time of 2.0 sec will provide the best overall performance but values between 1.6 to 2.0 sec will not significantly degrade performance.

LITERATURE SOURCES ABOUT DETECTION TECHNOLOGIES

This section involves a brief overview of each detector/technology being considered. Information about detector performance is provided in a later section. Detectors typically used at the stop line or upstream for advance detection that are of interest in this research project include:

- Inductive loops.
- Infrared cameras (with video detection systems).
- Magnetometers.
- Multiple technology detectors (hybrid).
- Microwave or Doppler radar.

Table 3. Typical Detection Designs in Texas (*16*).

Category	Design Speed (mph)	Design Element	Value
Detection layout	70	Distance from the stop line to the upstream edge of the advance detector, ft	600, 475, 350
	65	(Note: The number of distances listed indicates the number of advance detectors. All advance detectors are 6 ft in length.)	540, 430, 320
	60		475, 375, 275
	55		415, 320, 225
	50		350, 220
	45		330, 210
	45–70	Stop line detector length, ft	40
	45–70	Advance detector lead-ins wired to separate channel from stop line detectors	Yes
Controller settings	70	Passage (extension) time, s	1.2
	65	Detection mode	1.2
	60	Detector memory	1.4
	55	Stop line detector channel extend setting, s	1.2
	50	Stop line detector operation (deactivated or continuously active)[a]	2.0
	45		2.0
	45–70		Presence
	45–70		Nonlocking
	45–70		0.5 s
	45–70		Deactivated after gap-out

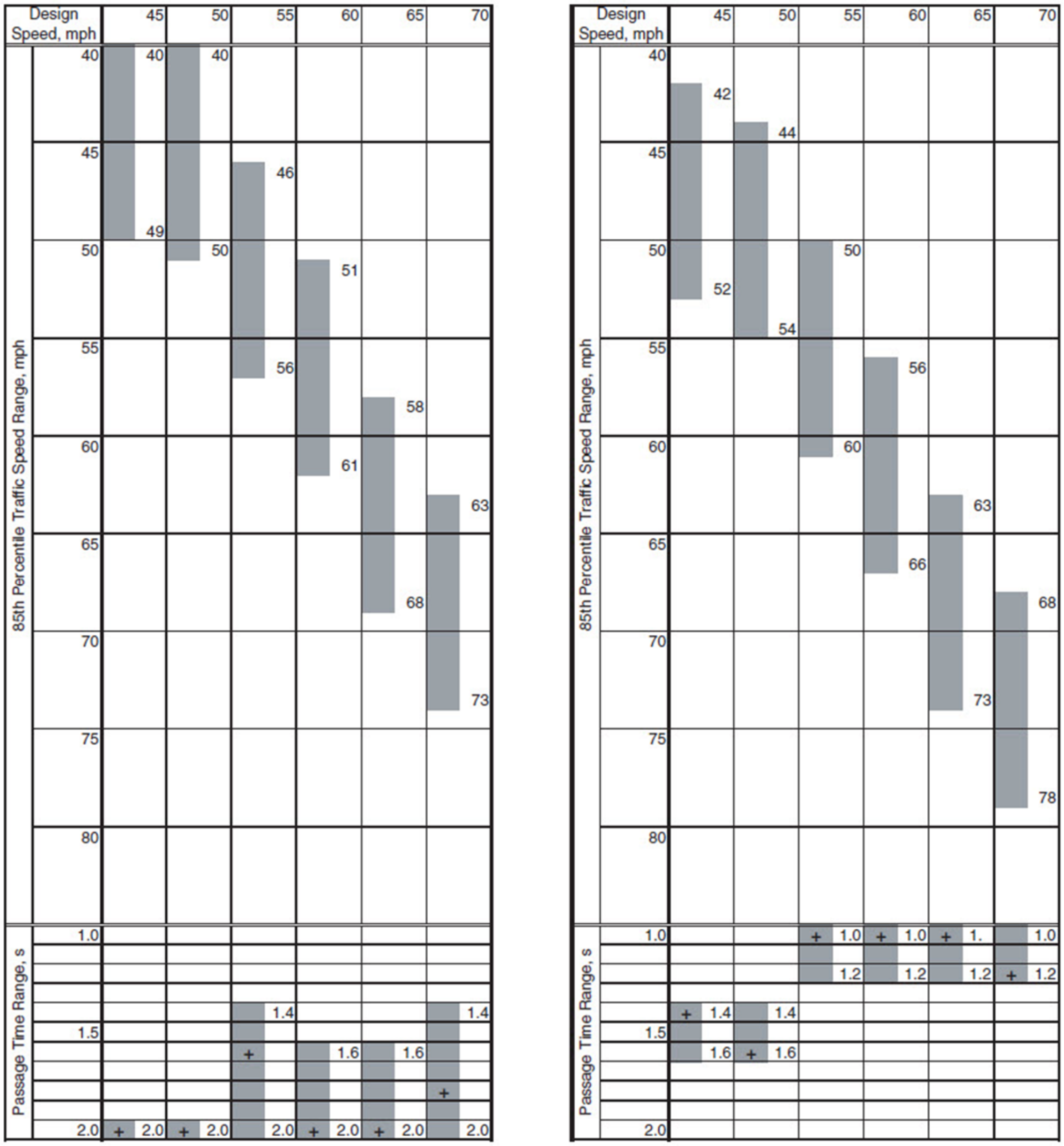
[a] Stop line detector operation is "deactivated" if it is disconnected after its detector channel extend timer times out. It is reconnected after the green interval terminates (see Special Detector, Operation Mode 4 in Eagle controller).

The reason for including inductive loops in this list is that some research documents the performance of test systems against inductive loops. In other words, if loops are installed and maintained properly, they often serve as ground truth for test detectors.

Table 4 lists the products being considered at the outset of this research. Reasons for including them include that they have not been fully investigated or they appear to offer improvements to current systems. Reasons for not including them later include tests of similar products are preferred and there is insufficient reason to test similar technologies or products.

Description of Stop Line Detection Systems

Stop line detection systems being considered are: two manufacturers of wireless magnetometers (Sensys Networks and the newer Trafficware Valence Pods) and one radar detector (Wavetronix SmartSensor Matrix). This section begins with a brief description of each detector before investigating research findings pertaining to their performance attributes.



"+" indicates desirable passage time.

(a) Stop line detector deactivated (b) Stop line detector active

Figure 7. Effective Passage Time Settings by Speed and Detector Operation (*19*).

Table 4. Candidate Detectors for Lab/Field Test.

Category	Detector/Technology	Stop Line	DZ Detection
1	Video Image Detection Aldis GridSmart [a] IR Cameras [a]	Primary Primary	Primary Secondary
2	Radar (Doppler or Microwave) Intersector by MS Sedco Wavetronix SmartSensor Advance Wavetronix SmartSensor Matrix	N/A N/A Primary	Primary Primary N/A
3	Multiple Technology Detectors (Hybrid) Iteris Vantage Vector Traficon TrafiRadar	Primary Primary	Primary Primary
4	Magnetometers Sensys Networks [b] Trafficware Valence Pods [b]	Primary Primary	Secondary Secondary

[a] Primary test will be stop line but could also serve DZ detection as well.

[b] Can monitor both stop line and DZ but not considered as good for DZ detection as stop line.

Video Image Detection

Aldis GridSmart®. The Aldis GridSmart video detection system has traditionally been known as a stop line detection system using a single fisheye lens camera positioned at or near a central point within the intersection. GridSmart is a dynamic vision-based intelligence software for traffic management, intended to reduce fuel consumption and vehicle emissions while reducing congestion through the use of a single camera. The Aldis website boasts the following features:

- Intersection counting.
- Intersection actuation.
- Pedestrian detection.
- Real time data.
- Horizon-to-horizon views (view entire intersection at one time).
- iPhone and iPad monitoring.

While the website does not appear to promote upstream detection with the same processor and different cameras, a company representative stated that Aldis does offer that capability. Based on this information, the Aldis is able to track vehicles on high-speed approaches using video cameras placed on each high-speed approach. The Aldis GridSmart system is deployed in 30 states around the United States and in 22 countries (*20*).

IR Cameras. Some of the conditions that traditional video cameras used for transportation purposes at signalized intersections need assistance to overcome include low light conditions, sun glare, and shadows. Thermal sensors appear to address some, or perhaps all, of these issues. They create imagery based on temperature differences, so thermal sensors need no light to work and are not blinded by direct sunlight.

Some examples of benefits derived from thermal imagers are provided below. Figure 8 contrasts the image provided by visible light cameras with thermal images where sun glare might be an issue for video image processing systems. Thermal sensors only respond to the heat signatures they detect.

Figure 8. Image Showing the Effects of Sun Glare (*21*).

Headlights present a challenge when using visible light cameras during low light conditions causing advance detection of the headlight bloom before the vehicle actually arrives. Besides triggering detections at the wrong time, headlight detection can cause false calls and missed calls. Figure 9 shows the side-by-side images.

Figure 9. Image Showing the Effects of Headlights (*21*).

Problems caused by shadows include missed detections and false detections. Video cameras can miss vehicles, pedestrians, cyclists, and even animals if they are in shadows. False detections sometimes occur when shadows cast from vehicles occupying adjacent lanes cross an unoccupied lane. Thermal sensors are usually better able to distinguish the desired objects due to their ability to sense heat, not light (see Figure 10).

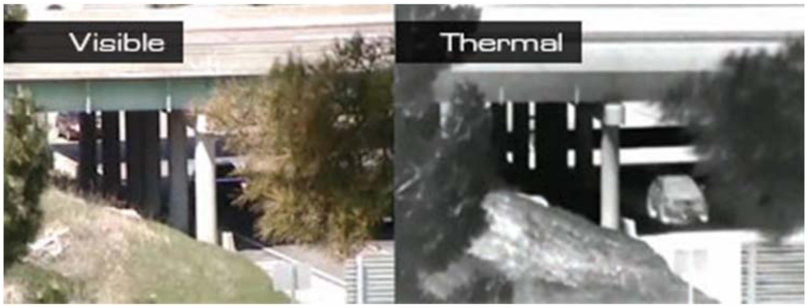


Figure 10. Image Showing the Effects of Shadows (*21*).

Sensys Networks Magnetometers. Sensys Networks offers a wireless vehicle detection system using magneto-resistive sensors installed in the pavement. Its features are as follows (*22*):

- 3-axis magnetometer.
- Sampling rate 128 Hz.
- 2-way radio communications with Sensys Networks Access Point.
- 10-year battery life.
- Reduced road closure time compared to loops.
- Patented, ultra-low "NanoPower" communications protocol.
- Universal platform for all traffic detection applications.
- Self-calibrating, self-tuning.
- Re-usable and remotely upgradeable.
- Capable of over 300 million detections.

Trafficware Magnetometers. The Trafficware "Valence Pod Detection System" is installed in the roadway and uses wireless communication to a central Access Point. The pods use a D-size lithium battery that is supposed to provide 10 years of life, assuming an average of 700 activations per hour, 24 hours per day. The lithium battery is replaceable.

The pod system uses the 900 MHz frequency band, providing a large range for detection and reliable communication with the ability to pass around obstructions such as building and foliage. It can also communicate through any water, ice, and snow that may collect over the sensor. The extended range removes the need for a repeater and reduces the number of components to streamline installation and making maintenance easier (*23*).

Installation of the pod in the pavement requires the following steps:

- Drill a hole in the pavement 4.0 inches in diameter by 2.75 inches deep.
- Place pod in a clamshell and install in cored hole.
- Backfill with epoxy.

Table 5 summarizes the features of the Pod detection system.

Table 5. Features of the Trafficware Detection System (*23*).

Features	
Magnetometer	Three-axis magnetometer for vehicle detection Extra Z-axis sensor for speed measurement Count, presence, and speed detection modes
Radio communications	Uniquely addressable and configurable Firmware can be upgraded wirelessly
Deployment	Can be deployed where other systems cannot be used, including with Split roadways High water tables Damaged pavement

Wavetronix SmartSensor Matrix. The Wavetronix SmartSensor (SS) Matrix generates 16 separate radar beams spaced in close proximity to create a 140-ft, 90-degree field of view. The sensor detects each vehicle within its field of view, knows its position and can predict subsequent movements. The configuration software is intuitive, using point and click functionality that facilitates fast setup in as little as 15 minutes. Full sensor installation only requires about an hour with the exception of pulling cable.

One strong feature of the SS Matrix is its immunity to weather and light conditions. According to the manufacturer, radar can propagate through rain, snow, fog, or dust storms without becoming distorted. Figure 11 shows the likely mounting locations for the SS Matrix, and the preference is as follows:

- Preferred: Near-side mast arm. This closer location to the monitored lanes takes full advantage of the sensor's 140-ft range and minimizes occlusion of left-turning vehicles.
- Alternate (for smaller intersections). Minimizes occlusion of left-turning traffic and minimizes traffic disruption during installation.
- Alternate-Flexibility. Minimize traffic disruption during installation.

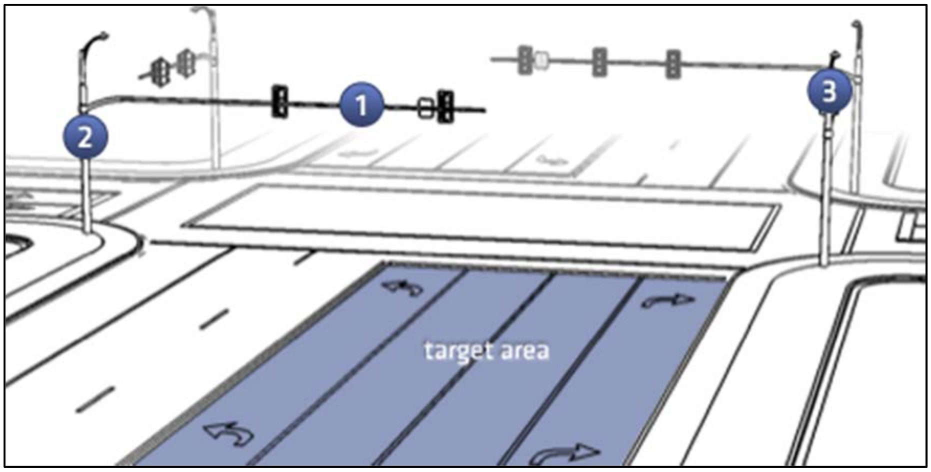


Figure 11. Likely Mounting Locations of the SS Matrix (*24*).

Pros of SmartSensor Matrix:

- Flexible mounting requirements.
- Intuitive user interface.
- Little or no effects of weather or light.
- Low maintenance.

Cons of SmartSensor Matrix:

- Initial cost is higher than competing technologies.

Description of Upstream Detection Systems

Multiple Technology Systems (Hybrids)

Iteris Vantage Vector. The Iteris Vantage Vector is a hybrid detector, using both video and radar to enhance detection. Iteris has offered video detection for many years, but its new detector adds radar to accomplish enhanced dilemma zone protection. Additional information provided by the hybrid sensor includes the number of vehicles, speed, and distance to vehicles in user configurable zones. Its features include (*25*):

- New graphical-user-interface (GUI) but maintains familiar video zone setup.
- Wi-Fi connectivity from roadside for laptop, netbook, or iPad®.
- Industry standard detection outputs.
- Aesthetic sensor with advanced design and color.
- Video detection to 400 ft.
- Radar detection to 600 ft.
- Vehicle tracking with directional discrimination.

Figure 12 shows the coverage area for the video and radar sensors.

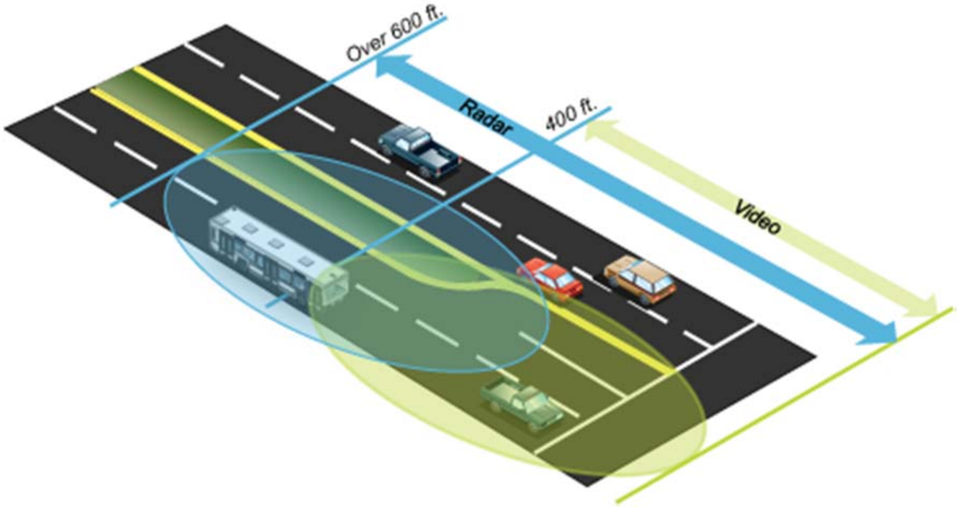


Figure 12. Detection Zone Layout for Iteris Vantage Vector Hybrid Detector (*25*).

Traficon TrafiRadar. The Traficon TrafiRadar is, in principal, similar to the Iteris Vantage Vector in that it is a hybrid detector incorporating both video and Doppler radar technologies. It uses video for detection nearer the stop line and radar for more distant detection (out to 600 ft). The radar provides information on the vehicle's lane position and speed in the specific area of interest, while the camera provides detection information on vehicle presence and counts at the stop line. Figure 13 illustrates the coverage of the camera and radar, indicating potential counting zones for the video component.

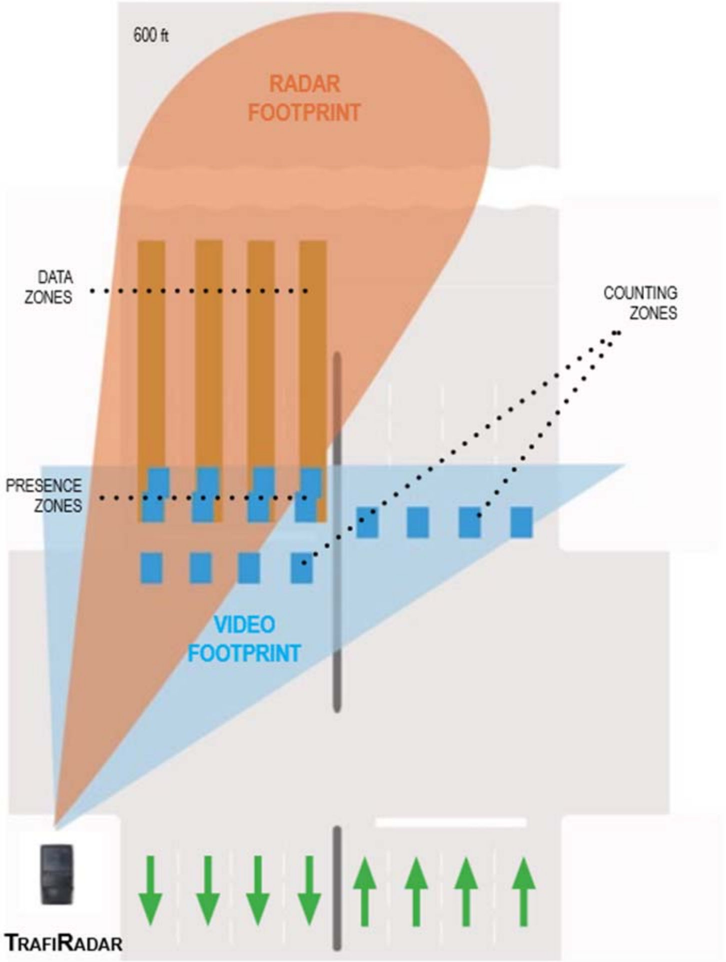


Figure 13. Detection Zone Layout for Traficon TrafiRadar Hybrid Detector (*26*).

Intersector Radar by MS Sedco. The Intersector is a microwave vehicle motion and presence tracking sensor used for advance detection at signalized intersections. Information from the manufacturer on specific details is limited, but the detector was included in other field studies referenced elsewhere in this document, thus justifying its inclusion here.

The Intersector uses FSK microwave radar to identify, classify, and track vehicles by position and speed. The user sets up detection zones based on an X-Y coordinate system. Users can set a maximum presence time and associate unique outputs, time delays, or output delays with individual zones. At least at first glance, the Intersector does not appear to have the same type of tracking vehicles and monitoring dilemma zone encroachments as the other radar sensors included in this document (*27*).

Wavetronix SmartSensor Advance. This description focuses on the SS Advance Extended Range instead of the original SS Advance because it has not been evaluated to the degree that the original detector has. Both units use a patented system for dynamic estimated time of arrival (ETA) tracking to continuously monitor the speed and position of individual vehicles. The newer SS Advance Extended Range adds an emphasis on trucks due to their different dilemma zones when compared to non-trucks. Its range is 900 ft for high profile vehicles such as commercial vehicles instead of 600 ft for the original detector. The SmartSensor Advance only places a call to the controller when vehicles meet the user-defined ranges, speeds, or ETAs. Figure 14 shows the mounting options for the newer sensor (on either mast arm or pole).

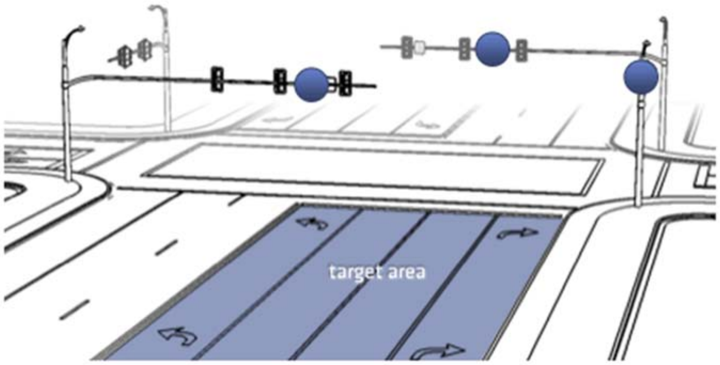


Figure 14. Mounting Locations of the SmartSensor Advance Extended Range (*28*).

LITERATURE SOURCES ABOUT DETECTION ACCURACY

The initial search did not find any objective sources that detailed the performance of the Iteris Vantage Vector detector system, the Traficon TrafiRadar, or Trafficware Valence Pod magnetometers. The following findings begin with literature sources that cover one technology or detection system, followed by sources that cover multiple systems in individual studies.

Single Technology or Detector Sources

Infrared Cameras

Lee describes the main characteristics of thermal traffic detection cameras and explains the reasons for being more efficient and cost effective than other control systems that use visible light imaging technologies. According to the article, thermal cameras make clear high contrast images from the radiated heat energy, which is abundant in the environment compared to visible light. This allows the cameras to more easily detect objects than traditional light cameras, and therefore their performance is not greatly affected by the sunlight, nighttime headlight glare, reflections off wet surfaces, deep shadows, smoke, or dust. Specifically, IR cameras create pictures from differences in heat and every object with a temperature over −273°C produces thermal energy that can be detected and turned into an image. Additionally, adverse weather conditions such as heavy fog and snow may degrade the image quality of thermal cameras but not to the same extent as conventional cameras, which can be of limited use under similar conditions. Moreover, thermal cameras are environmentally friendly as they do not need lights to work, yielding cost savings for an agency, decreasing light pollution, and minimizing vehicle exhaust emissions by optimizing traffic flows. As far as the installation system is concerned, thermal cameras are compatible with the mechanical and electrical systems used by conventional closed-circuit television (CCTV) cameras sharing the same hardware, mounting kits, cabling, processors, input power, output signal, Ethernet transmission, and voice-over-Internet Protocol (VOIP) systems. Due to the above characteristics, thermal cameras have numerous applications such as incident detection, vehicle counting, tunnel safety, pedestrian detection, construction zone safety, and many more (*29*).

In 2012, Grossman et al. compared the performance of traditional video cameras against that of two thermal image sensors for stop bar presence detection by using inductive loop detector data for baseline data to compare the three systems. The authors adopted Indiana's test protocol which includes four performance metrics:

- Number of missed detections greater than a prescribed threshold.
- Number of false detections greater than a prescribed threshold.
- Statistical bias and dispersion of detection zone activation point relative to the intended start of a detection zone.
- Statistical bias and dispersion of detection zone deactivation point relative to the intended end of a detection zone.

Study periods evaluating the bias in activation and termination times included day and night conditions. The camera and the sensors were installed on the westbound and northbound approaches of a signalized intersection in Indiana for 24 hours (*30*).

The loop detection layout met Indiana Department of Transportation (InDOT) standards and included four 6-ft loops at 15 ft on center spacing for a nominal detection area of 51 ft. The three systems deployed included Autoscope video, a Wireless Technology Inc. (WTI) thermal sensor (C-Max Ultra Series), and a FLIR Systems Inc. (FLIR) thermal sensor (SR-334T). The thermal sensors were uncooled vanadium oxide microbolometer sensors operated at 7.5 to 15.5 micrometer wavelengths with resolutions of 320 × 240 pixels and 30 frames per second NTSC video output. All three devices were mounted side by side on a luminaire arm, approximately 25 ft above grade. Each of the cameras and sensors sent raw video via coaxial cable to a processing unit in a signal cabinet. The devices did not have onboard processing or any type of control communications. The detector calls were made by the processing units and logged to a database on the signal controller. Output video feeds were sent to a video encoder and saved to a hard drive in the cabinet. The video showed the detection zone layout and the status of the detector calls for each approach and device. The data files were then saved in a SQL database for further processing and analysis (*30*).

The results of the analysis showed that no missed call events longer than 10 sec occurred and only a small number of false calls occurred. Sources of false calls for each of the video-based systems included: large vehicles, shadows (thermal and visible light camera), headlight glare (visible camera only), and other physical and natural obstacles that hide adjacent detection zones. One of the most significant findings was that, in the case of the video camera, the activation times of a detection system under daytime and nighttime operations differ by approximately 1 sec. The main reason behind this lag is the vehicle headlight projections that affect the video quality. On the other hand, the thermal cameras resulted in negligible differences in the median activation times during day and night conditions. This promising finding suggests that integrating cameras sensitive to the infrared spectrum could improve the quality of the nighttime video detection (*30*).

Iwasaki et al. developed an algorithm for stop line detection using thermal images taken with infrared cameras. According to this method, the windshield of a vehicle and its surroundings are considered as the target of pattern recognition. The vehicle detection process involves several steps. The goal of the first step is to specify the area of moving vehicles. This is achieved by estimating standard deviations of pixel values along the time direction of spatio-temporal images. In the second step, vehicle positions are determined by applying a pattern recognition algorithm that uses Haar-like features for each frame of an image. The third step involves applying a series of procedures to correct misrecognized vehicles. Lastly, the proposed method combines the spatio-temporal image processing and vehicle pattern recognition in the same frame to specify vehicle positions and classify their movements. The vehicle speeds are classified based on the ratio of the area of the moving vehicle in the rectangle that shows the vehicle's windshield and its surroundings. Three classes of speeds are defined: zero speed (stopped vehicles), low-speed, and high speed (*31*).

In order to test the effectiveness of the proposed method, the authors conducted experiments using 20,984 positive and 9,500 negative samples of images. The images, recorded by an infrared thermography camera TVS-200, were transmitted to a personal computer with a 1/60-sec interval through a IEEE1394 cable. The size of the images was 320 × 240 pixels, and each pixel had 256 gray levels. The whole system was installed on a pedestrian bridge with the thermal camera recording the traffic conditions on the roadway segment under the bridge. Results showed that the algorithm detected 574 of 596 vehicles—that is a 96.3 percent detection rate (*31*).

The authors also developed a method for estimating traffic flow conditions using the results obtained by the proposed algorithm. This method is based on the number of vehicles in the examined area and the degree of movement of each vehicle. The method can be used for automatic traffic flow monitoring, detection of incidents and parked vehicles, as well as for traffic signal control (*31*).

Building upon their previous work, Iwasaki et al. presented two methods for vehicle stop bar detection using thermal images taken with infrared cameras under various weather conditions. The first method, originally presented in 2011, detected vehicles under different environmental conditions involving poor visibility conditions in snow and thick fog. The windshield and its surroundings were considered as the target of pattern recognition. Detection used two infrared thermal cameras, TVS-500EX and TVS-200. For the TVC-500EX, the images were transmitted to a personal computer with a 1/60-sec interval through a USB 2.0 cable. Similar to their previous study, the size of the images was 320 × 240 pixels, and each pixel had 256 gray levels. The frame rate, the frame size, and the number of gray levels of the TVS-200 were the same as those of the TVS-500EX, but the cable that connected the camera and the computer was different (IEEE1394) (*32*).

As explained in their previous study, the vehicle detection process involved spatio-temporal image processing by estimating standard deviations of pixel values, vehicle pattern recognition, and correction procedures for misrecognized vehicles. These experiments used positive samples of images that were taken during June, August, and October. The results revealed a satisfactory detection rate of 96.2 percent. One finding of the study was that during these months, the temperature of the windshield was typically lower than that of the exterior of the windshield. On the other hand, the opposite effect typically occurs during cold months, so negative samples of the original images are better. Another finding was that in low temperatures above the freezing point, the detection accuracy significantly decreased because the difference in temperature between the windshield and its exterior was small (*32*).

Based on these findings, Iwasaki et al. developed a second method to overcome the limitations explained above. This method is based on tire thermal energy that is reflected on the road surface. The principle of the method is that the temperature of the tires and that of the road surface are considerably different during cold weather conditions (e.g., in winter). This yielded a high vehicle pattern recognition (92.8 percent) that cannot be achieved by the first method. By combining the two methods, the overall accuracy of vehicle detection was improved under various environmental conditions. Lastly, similar to their previous work, the authors demonstrated an example of how traffic information obtained from the two methods could be applied to automatic traffic flow monitoring and traffic signal control (*32*).

SmartSensor Matrix

Table 6 summarizes the count accuracy of the SmartSensor Matrix at an intersection with a four lane approach and a posted speed limit of 35 mph, as depicted in Figure 15. Since the count was performed by the manufacturer, the results need to be verified by an objective party. Another test at 45 mph and count zones placed back from the stop line indicated better results with total count accuracy of 92.6 percent. A third test at a mid-block location at 45 mph was even better, with overall count accuracy of 99.7 percent (*33*).

Table 6. Count Accuracy of Wavetronix SmartSensor Matrix at Stop Line (*33*).

Lane	**Vehicle Counts**		**Count Accuracy**
	Sensor	**Truth**	
1	36	42	85.7%
2	36	50	72.0%
3	33	38	86.8%
4	31	39	79.5%
Total	136	169	80.5%

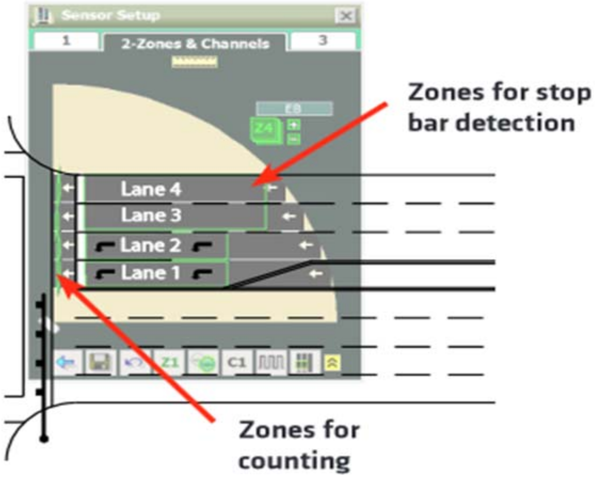


Figure 15. Configuration of the SS Matrix for Counting Vehicles at Stop Line (*33*).

Trafficware Pod

The initial search did not discover any objective evaluations of the Trafficware Pod magnetometer system.

Wavetronix SmartSensor Advance

Middleton et al. conducted a field study using the original SS Advance (not the Extended Range) that emphasized finding alternatives to intersection detection to replace video systems, so that research compared results of the Wavetronix Advance with a video system. The project positioned the Wavetronix SS Advance at the following two locations: at the stop line and at 175 ft upstream of the stop line. Placing it 175 ft upstream of the stop line resulted in an average increase of about 23 percent in the number of phase terminations compared to video detection. The improved ability of the Advance to detect gaps compared to video translated into more phase terminations. Red-light running within the first 2 sec after the onset of red decreased by an average of 4.81 percent and increased by an average of 0.67 percent between 2 and 4 sec after red start on phase 2 compared to video detection. The evidence suggests that the increase in red-light-running between 2 to 4 sec after the onset of red was due to the passage time of 200 milliseconds in the controller for the main street phases being too short and/or the dilemma zone travel time range of 2.5 to 5.5 sec requiring a wider range of perhaps 2.0 to 6.0 sec due to the large number of trucks. The initial data analysis immediately following data collection did not provide sufficient clues to suggest that a problem existed, so the discovery of this problem came too late to recollect the data with improved settings (*34*).

For phase 6, when the Advance was 175 ft upstream of the stop line, there was a 48 percent increase in phase terminations per day while the SS-200 detector was in use compared to video detection. Red-light running within the first 2 sec increased by 2.43 percent when the SS-200 detector was in use compared to video. Again, researchers believe the increase was due to the 200 milliseconds of passage time in the controller for this phase and the dilemma zone lower and upper travel time boundaries of 2.5 to 5.5 sec. There was an increase of 0.91 percent in red-light-running between 2 and 4 sec after the onset of red when the SS-200 controlled the intersection compared to when video controlled the intersection.

Moving the Advance to the stop line resulted in a smaller average increase in the number of phase terminations of about 18 percent per day for phase 2. Also, the number of red-light-runners within the first 2 sec after the onset of red decreased by 0.76 percent, and the number of red-light-runners within 2 to 4 sec after the onset of red also decreased by 0.68 percent. For phase 6, results at the stop line indicated an average increase of around 12 percent in the number of terminations per day. The number of red-light-runners within the first 2 sec of red decreased by 0.03 percent, while the number of red-light-runners between 2 sec and 4 sec of red increased by 0.07 percent when the SS-200 detector controlled the intersection.

Results indicated that the reliability of this detector based on limited testing was commendable. Even in excellent weather and during the daytime, its performance rivaled that of video. Since weather and lighting are not factors in its performance, it would far outperform video in less ideal conditions. Its installation causes little or no traffic disruption since it mounts beside and above the roadway (*34*).

Multiple Technology or Detector Sources

Detector Performance in Inclement Weather

One issue that traffic signal maintenance practitioners must consider is that of detection quality during adverse conditions. These conditions may include inclement weather events such as wind, rain, or snow; lighting condition changes like shadows, night, or excessive sun glare occurring when the sun is on the horizon and aligned with the intersection approach being monitored; or combinations of weather and lighting condition issues (e.g., night and rain, which involves significant headlight glare on the pavement). Various newer detection technologies have been tested for performance under such conditions. These technologies include radar units, infrared cameras, combination video/radar cameras, and in-pavement wireless magnetometers (e.g., Sensys Networks magnetometers). The following sections summarize the evaluations of these technologies.

Medina et al. evaluated several types of detectors under normal weather conditions and several different types of inclement weather conditions (*35, 36, 37*). They conducted these tests at a signalized intersection approach that consisted of two exclusive left-turn lanes and a shared through/right-turn lane and had existing inductive loops that could be used to obtain a comparison dataset. Their evaluation included both stop line and advance detection applications. The stop line detectors were located 2 ft back from the stop line, while the advance detectors were located 264 ft back from the stop line. They evaluated the detection systems based on the following measures:

- False calls, including:
    - Calls received when no vehicle is present.
    - Calls received when a vehicle is present in the adjacent lane but not the observed lane.
    - Multiple calls received due to flickering when only one vehicle is present but a call is dropped and immediately restored.
- Missed calls, including:
    - Vehicles passing between two monitored lanes.
    - Vehicles passing directly through the detection zone.
- Stuck-on calls (i.e., calls that do not end when the vehicle leaves the detection zone).
- Dropped calls (i.e., calls that end while the vehicle is still present in the detection zone).

Medina et al. explained that false calls can lead to operational inefficiency because they can cause unneeded movements to be provided with a green signal indication. Similarly, stuck-on calls can degrade efficiency by forcing movements to be provided with green longer than needed. False or stuck-on calls can also compromise safety if they cause high-speed movements to max out, in which case the green indication is ended regardless of whether vehicles are present in the indecision zone. Missed or dropped calls can compromise safety because drivers who do not receive service for excessive periods of time may proceed against a red signal indication.

In their tests, Medina et al. counted the frequency of the preceding measures for the Sensys in-pavement magnetometer and microwave radar detectors manufactured by Intersector and Wavetronix under different weather conditions for both stop line and advance detection applications. For all sensors, they allowed the vendor to check the installation and make tweaks as needed to ensure optimal performance. They collected evaluation datasets before and after vendor modifications, but results herein only use the data collected after modification.

They defined the false call and stuck-on call rates as the frequency of those measures divided by the number of actuations of the respective detector. They defined the missed call and dropped call rates as the frequency of those measures divided by the number of loop-detector actuations. An aggregation of their results derived from several sources (*35, 36, 37*) is provided in Table 7.

Table 7. Aggregated Results of Detector Tests by Weather Condition (*35, 36, 37*).

Sensor Type	Weather	Detection Location	Failure Rate, %, by Failure Type			
			False Call	Missed Call	Stuck-On Call	Dropped Call
Sensys	Normal	Stop line	15	0	0	0
		Advance	2	3	0	0
	Snow	Stop line	17	0	0	0
		Advance	2	3	0	0
	Rain	Stop line	12	0	0	0
		Advance	1	5	0	0
Intersector	Normal	Stop line	4	0	2	0
		Advance	1	8	0	0
	Wind	Stop line	2	0	2	0
		Advance	0	5	0	0
	Snow	Stop line	6	0	2	0
		Advance	1	7	0	0
	Rain	Stop line	2	0	4	0
		Advance	1	11	0	0
Wavetronix [a]	Normal	Stop line	1	2	0	0
		Advance	11	1	0	0
	Wind	Stop line	1	1	0	0
		Advance	0	0	0	0
	Snow	Stop line	48	8	1	0
		Advance	30	2	0	0
	Rain	Stop line	7	2	0	0
		Advance	17	1	0	0

[a] The Wavetronix system consisted of one SmartSensor Matrix unit for the stop line and one SmartSensor Advance unit for the advance zones.

Overall, the most common failure type was false call, which typically happens more often at the stop line than at the advance detection zones. The Sensys detector was generally found to have the highest false-call rate, with many of these false calls being the "flickering" type. Medina et al. did not offer an explanation for the notable numbers of false calls with the Sensys detectors. They did document several issues with hardware reliability that required the vendor to replace components, but these issues occurred before the collection of the evaluation data.

Additionally, the Wavetronix detector exhibited a very high false-call rate in snowy conditions. Medina et al. observed that the snow periods used in their evaluation also sometimes experienced a notable amount of wind, so they opined that the combination of wind and snow was problematic for the Wavetronix detector. However, they also noted that, at their test site, the Wavetronix detector was mounted on the signal mast arm while the Intersector detector was mounted on the signal pole. Hence, the Wavetronix detector was more affected by mast-arm swaying than the Intersector detector.

Medina et al. conducted a similar evaluation of three different video detection cameras (Autoscope, Peek, and Iteris) using the same test site (*38*) and the same methodologies that they applied in previous efforts (*35, 36, 37*). The cameras were all mounted on a luminaire at the intersection, so there were no issues with wind swaying or differences in mounting locations. The purpose of this effort was to compare the three cameras in the following conditions:

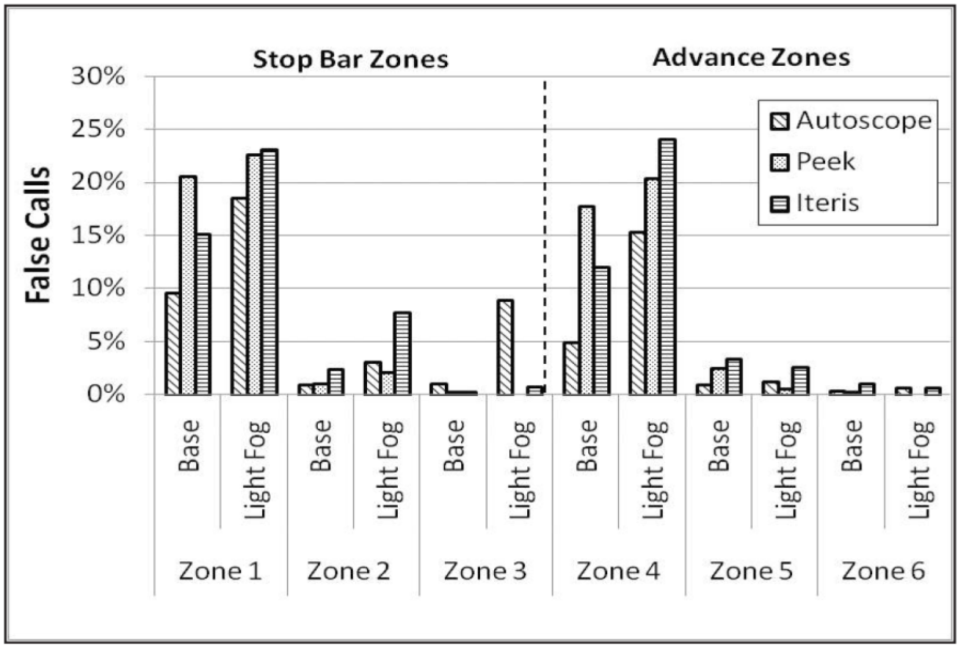
- Base conditions (daytime or nighttime as appropriate, no inclement weather).
- Light fog in daytime.
- Dense fog in daytime.
- Rain in daytime.
- Snow in daytime.
- Rain in nighttime.
- Snow in nighttime.

Medina et al. presented their results for three stop-line detection zones numbered 1–3 and three advance detection zones numbered 4–6, as there are three lanes on the intersection approach. Zones 1 and 4 correspond to the innermost lane.

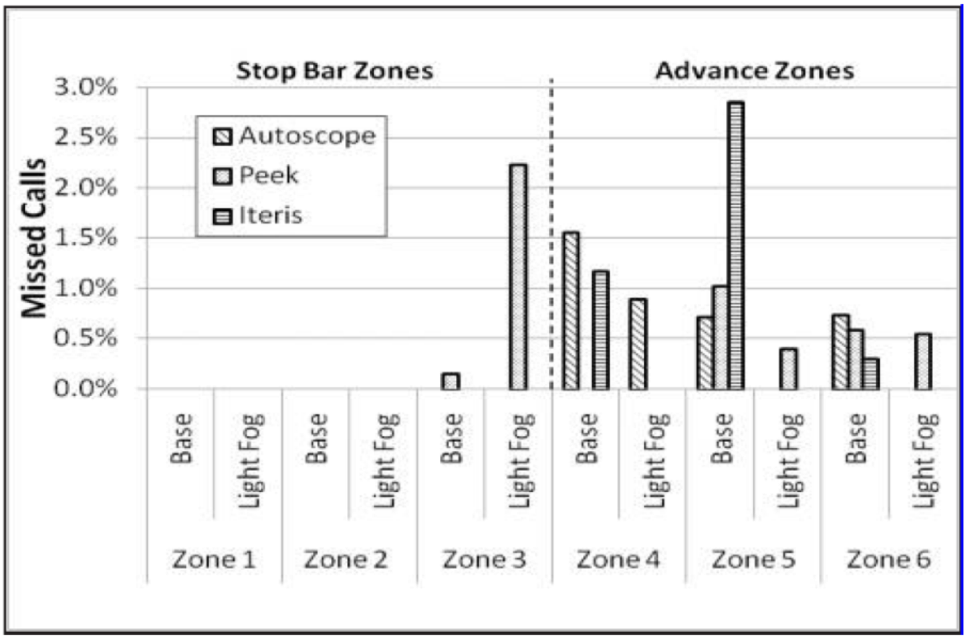
The results of the analysis of light fog conditions are shown in Figure 16. Several trends are evident. First, false calls were most prevalent in zones 1 and 4 due to occlusion, as these zones are located in the innermost traffic lanes. Second, all three camera types showed a general increase in both false and missed call rates during light fog conditions compared to base conditions. Third, the missed call rate was notable in the advance zones for all three camera types. Please note that the vertical axis ranges vary for the following graphics.

The results of the analysis of dense fog conditions are shown in Figure 17. Note that the results for base conditions in Figure 17 are identical to those in Figure 16, though the *y*-axis ranges are slightly different. It can be seen that the rate of false calls decreased in the innermost detection zones but increased elsewhere, while the rate of missed calls generally increased, especially at the advance zones. The occurrence of dense fog led to more vehicles being overlooked by the video detection cameras.

The results of the analysis of daytime rain conditions are shown in Figure 18. For all three cameras, the rate of false calls generally increased, and the rate of missed calls generally decreased compared to base conditions. Media et al. observed that during the time periods experiencing daytime rain, most vehicles' headlights were on. Headlight reflections on the pavement created better contrast and reduced the frequency of missed calls but also increased the frequency of false calls.



a. False Calls



b. Missed Calls

Figure 16. False and Missed Call Rates for Light Fog Conditions (*38*).

The results of the analysis of daytime snow conditions are shown in Figure 19. The occurrence of snow in the daytime is shown to cause notable increases in false calls at all zones and missed calls at the advance zones. Medina et al. stated that the video footage did exhibit camera movement due to wind, so the number of “flickering” false calls increased due to vehicles being detected multiple times. They further stated that the camera lenses were not blocked by ice.

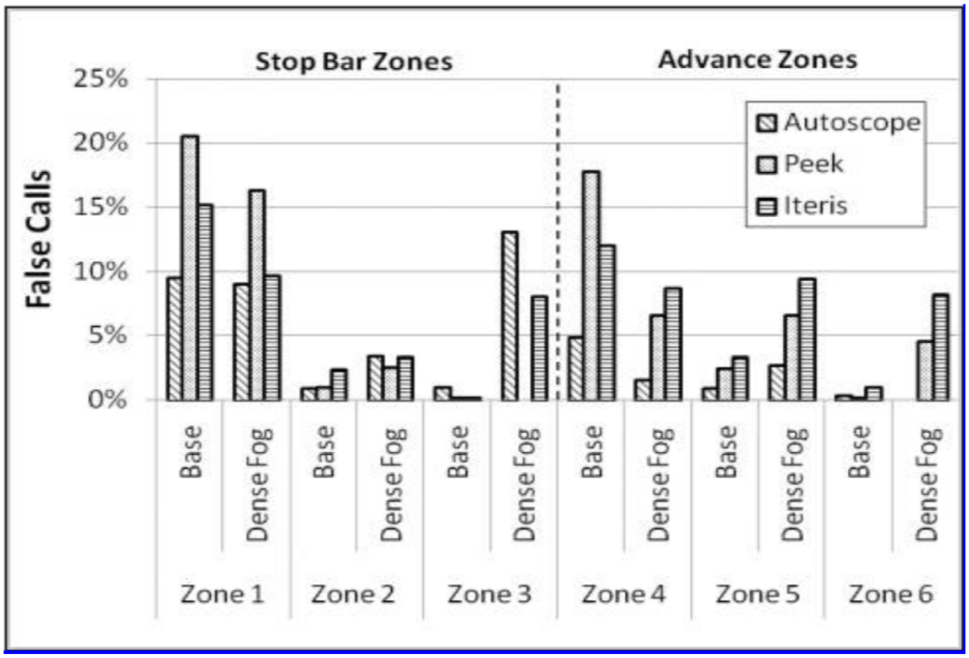
Hence, the problem with false calls is attributable to the snow as well as the wind that accompanied the snowy conditions.

Figure 20 shows the results of the analysis of nighttime rain conditions. Note that the base conditions for this comparison were nighttime periods with no inclement weather; conversely, the base conditions in the previously-shown comparisons were daytime periods with no inclement weather. It is evident that the rate of false calls increased at all detection zones due to headlight glare and reflections on the pavement.

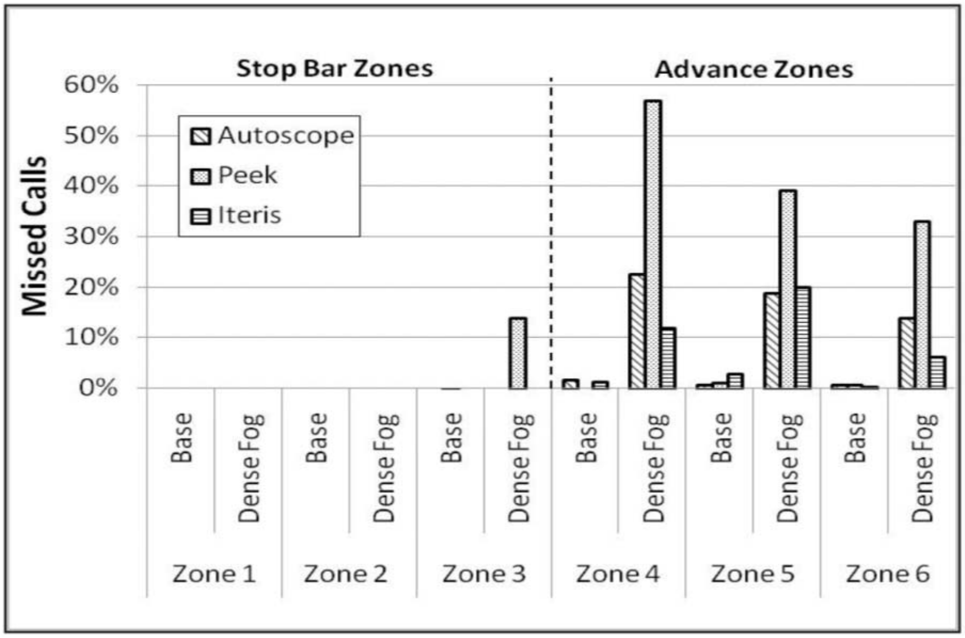
Figure 21 shows the results of the analysis of nighttime snow conditions. A comparison is provided only for false calls, as missed calls did not change significantly. Figure 21 shows that false calls increased at all six detection zones during the nighttime snow conditions compared to the base conditions. As was the case with the analysis of daytime snow conditions (see Figure 19), the nighttime snow conditions also experienced notable amounts of wind. Examination of the video footage found that many flickering false calls occurred as a result of camera movement and the same vehicle being detected multiple times.

The analysis reported by Medina et al. (*38*) clearly shows that video detection performance degrades under adverse weather conditions, during both daytime and nighttime. In an effort to overcome these issues, Iwasaki et al. examined the effectiveness of infrared cameras in poor-visibility conditions (*39*). They started their exploration by capturing footage of approaching vehicles in snowy and foggy weather and demonstrated that infrared cameras could clearly distinguish the thermal pattern of approaching vehicles even though only the vehicles' fog lights could be seen by a visible-light camera. Iwasaki et al. examined multiple images of vehicles and determined that vehicles' windshields typically offer a prominent target for infrared cameras because their temperature usually differs notably from the temperature of their surroundings. Based on these observations, they developed an algorithm to process infrared images and count vehicles as well as classify them as stopped, moving slowly, or moving quickly. They collected video and infrared footage of vehicles on a traffic signal approach under normal weather conditions and found that the false-call and missed-call rates for their algorithm are 1.3 percent and 3.7 percent, respectively.

The algorithm developed by Iwasaki et al. (*39*) was found to be effective most times of the year. However, they found that during certain times of the year, particularly winter, the temperatures of vehicles' windshields are often similar to that of their surroundings (*40*). In this case, windshields cannot be used to detect vehicles reliably with an infrared camera. To overcome this limitation, Iwasaki et al. developed another algorithm that detects vehicles by identifying the thermal energy reflection from their tires. They tested this algorithm and found that it has a false-call rate of 3.4 percent and a missed-call rate of 7.2 percent. They stated that they intend to refine the tire-based algorithm further in future efforts.

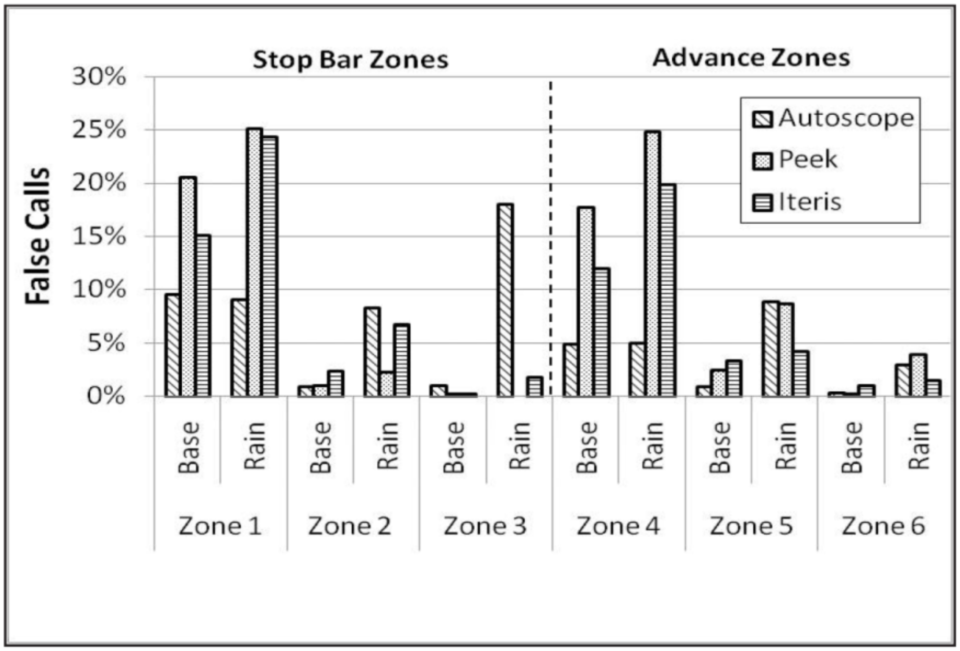


a. False Calls

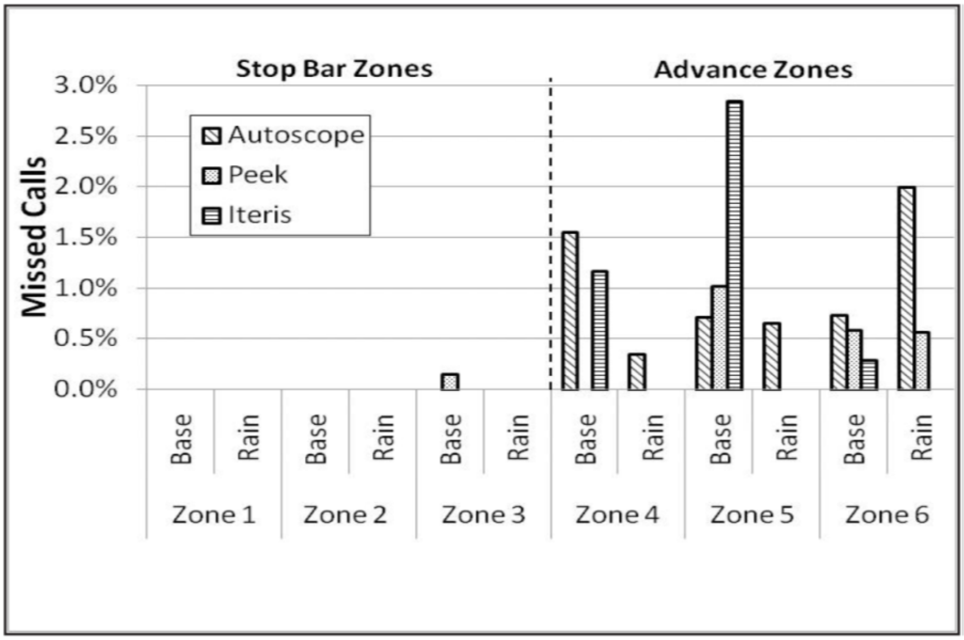


b. Missed Calls

Figure 17. False and Missed Call Rates for Dense Fog Conditions (*38*).

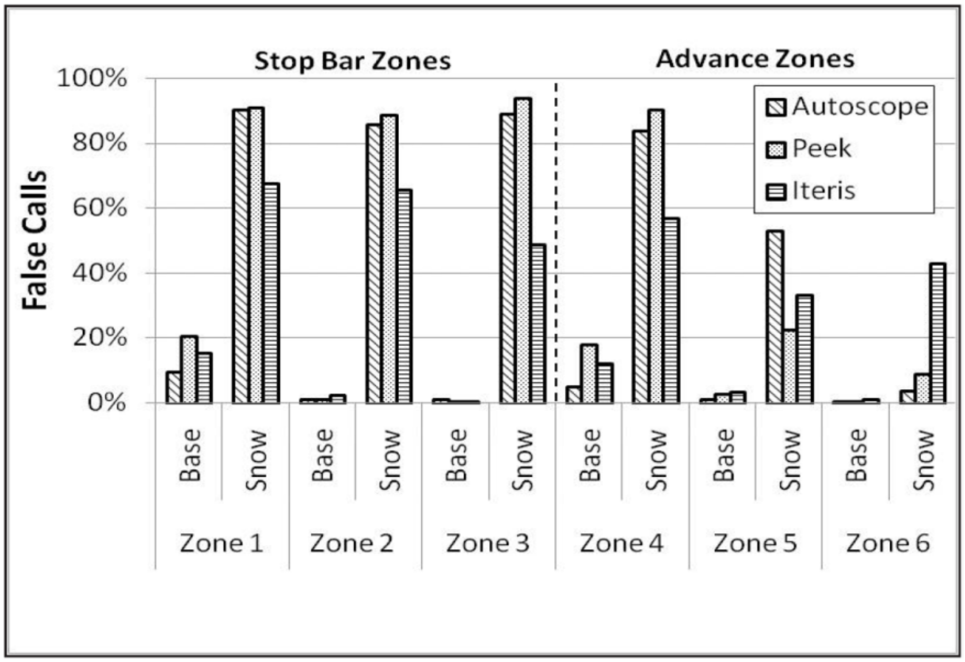


a. False Calls

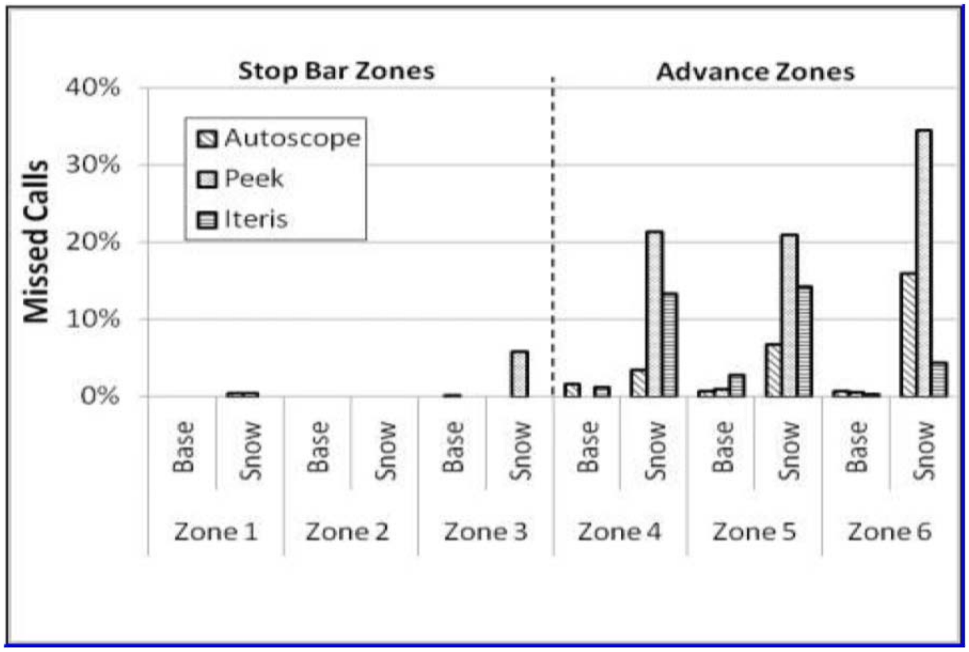


b. Missed Calls

Figure 18. False and Missed Call Rates for Daytime Rain Conditions (*38*).

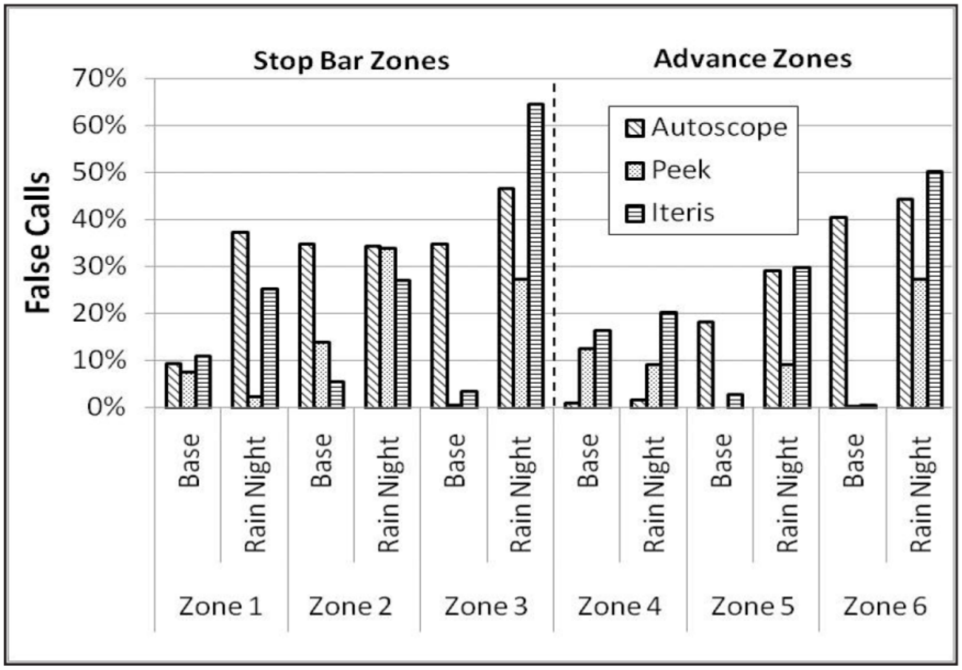


a. False Calls

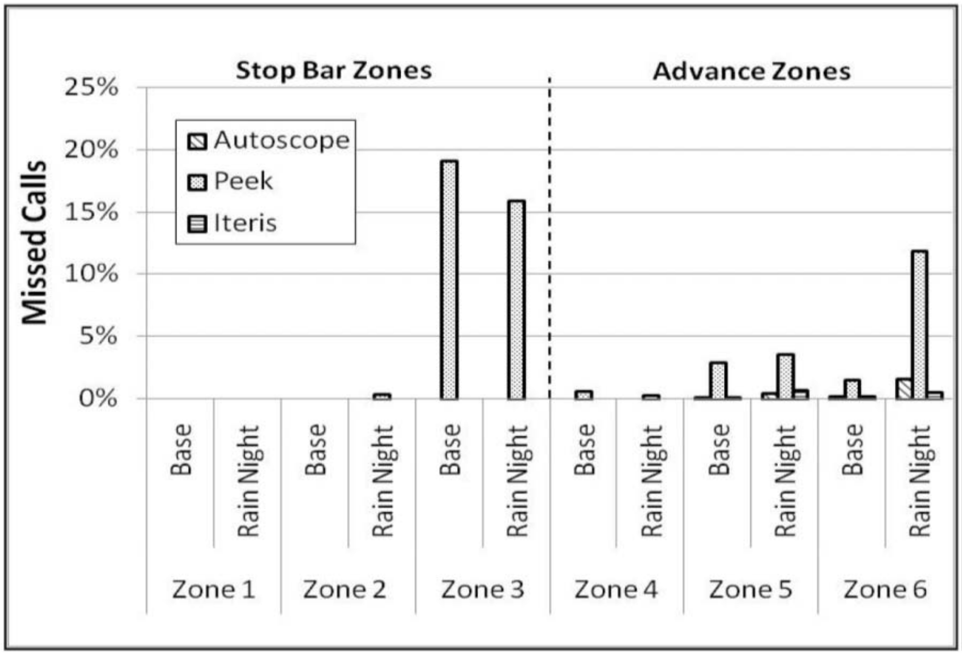


b. Missed Calls

Figure 19. False and Missed Call Rates for Daytime Snow Conditions (*38*).



a. False Calls



b. Missed Calls

Figure 20. False and Missed Call Rates for Nighttime Rain Conditions (38).

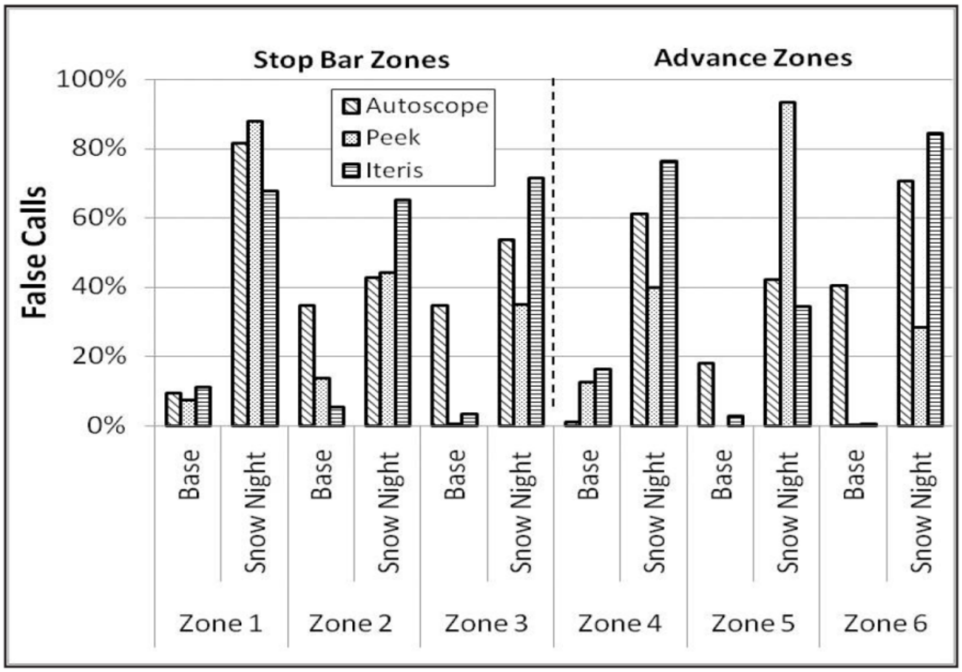


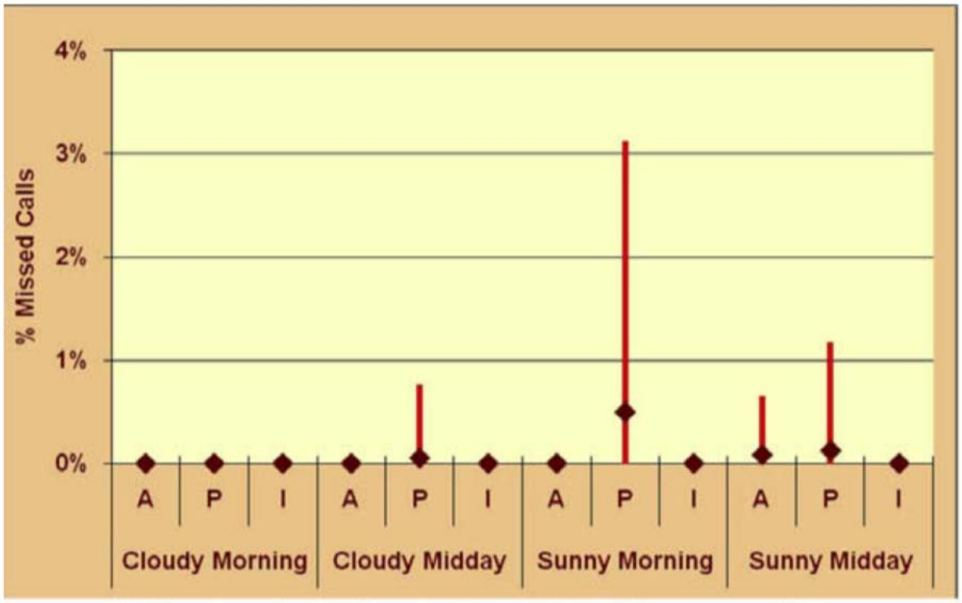
Figure 21. False Call Rates for Nighttime Snow Conditions (*38*).

Detector Performance in Adverse Lighting Conditions

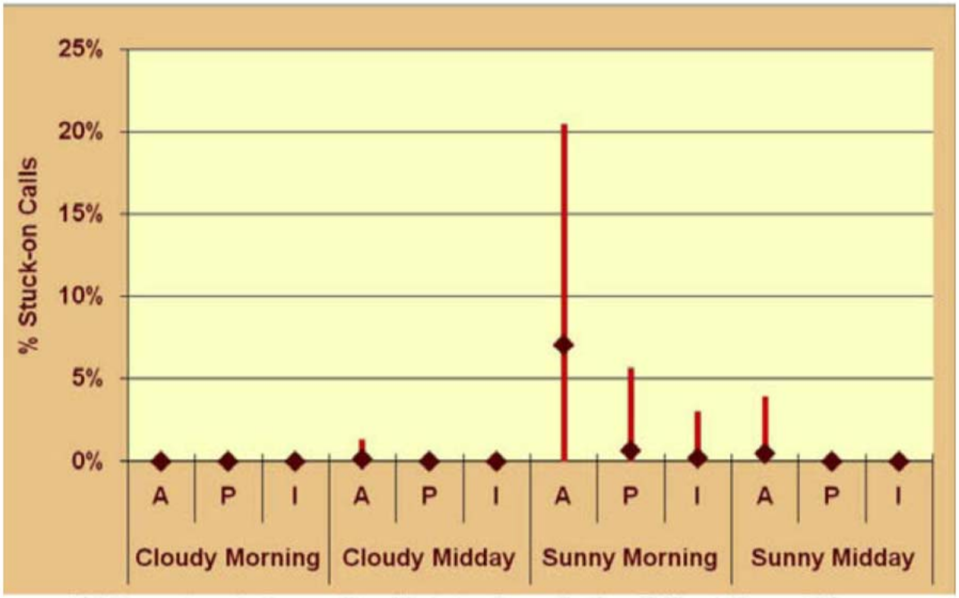
The previously-summarized work of Medina et al. (*38*) focused on lighting conditions as well as weather conditions. In addition to this work, Chitturi et al. also conducted an analysis of the effect of shadows and time-of-day lighting conditions on video detection accuracy (*41*). Like the analysis described by Medina et al. (*38*), this analysis involved cameras manufactured by Autoscope, Peek, and Iteris, and the measures of false calls, missed calls, stuck-on calls, and dropped calls. Their analysis results for missed and stuck-on call rates at the stop line detection zones are shown in Figure 22. The data points in the graphs represent the average rates across the three stop-line detection zones, and the bars represent the ranges.

Chitturi et al. examined the video footage to determine the reasons for the missed calls in Figure 22a. They found that all missed calls were for dark-colored vehicles. The increase in stuck-on calls shown in Figure 22b for the sunny morning condition was caused by the shadow of the signal mast arm. In the morning period, shadows were longer than in midday, and shadows were more prominent in sunny conditions than in cloudy conditions.

The analysis of false-call rates by Chitturi et al. is plotted in Figure 23. Note that the *y*-axis ranges are different for the three graphs. For all four conditions (cloudy morning, cloudy midday, sunny morning, and sunny midday), the false-call rate is very low (never more than 4 percent) for zone 3, which is the outermost lane on the approach. No shadows from adjacent lanes are cast onto this lane during the morning or midday periods, so false calls were rare. Zones 1 and 2 showed somewhat higher false-call rates, partly because of shadow occlusion from adjacent lanes, and partly because of various other events, which included crossing or turning vehicles, pedestrians, or even exhaust fume clouds. The false calls from crossing vehicles and pedestrians occurred even though the directionality function in the video detection cameras was turned on (*41*).

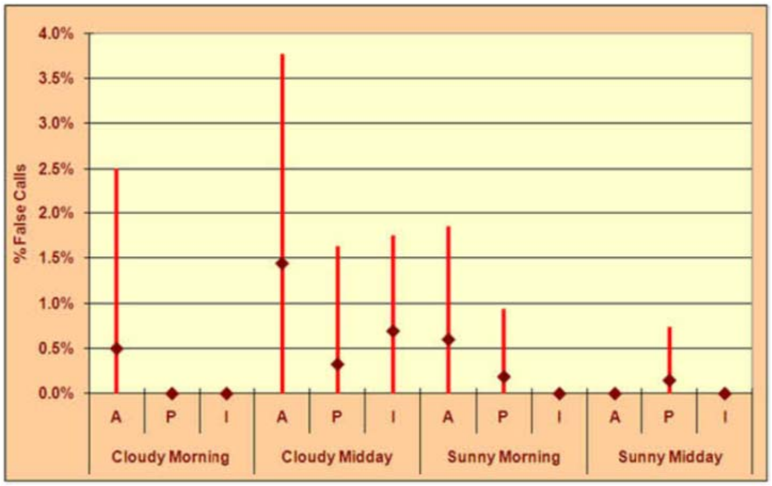


a. Percentage Missed Calls at Stop Bar under Four Different Day Conditions

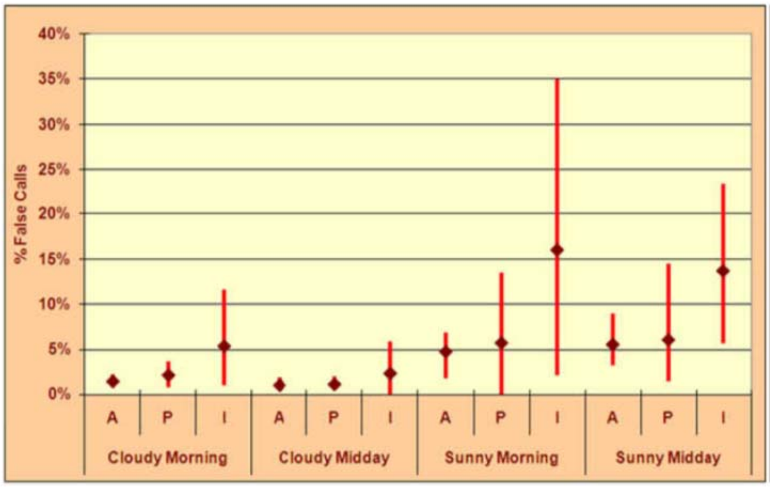


b. Percentage Stuck-On Calls at Stop Bar under Four Different Day Conditions

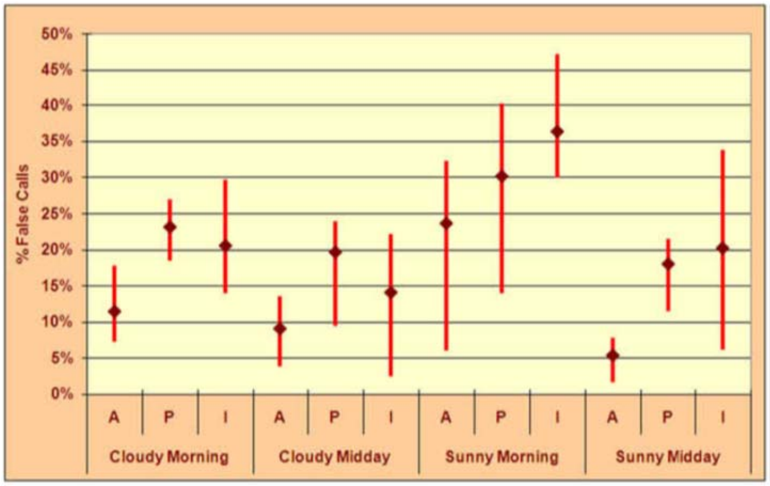
Figure 22. Missed and Stuck-On Stop-Line Call Rates by Light Condition (*41*).



a. False Calls for Zone 3



b. False Calls for Zone 2



c. False Calls for Zone 1

Figure 23. False Call Rates by Light Condition and Detection Zone (*41*).

LITERATURE SOURCES ABOUT FIELD TESTS AND TEST PROCEDURES

Medina et al. evaluated several types of detectors and used test metrics that would work well in other research endeavors such as this one (*35, 36, 37*). They evaluated the detection systems based on the following measures:

- False calls, including:
  - Calls received when no vehicle is present.
  - Calls received when a vehicle is present in the adjacent lane but not the observed lane.
  - Multiple calls received due to flickering when only one vehicle is present.
- Missed calls, including:
  - Vehicles passing between two monitored lanes.
  - Vehicles passing directly through the detection zone.
- Stuck-on calls (i.e., calls that do not end when the vehicle leaves the detection zone).
- Dropped calls (i.e., calls that end while the vehicle is still present in the detection zone).

The two classes of detectors covered by Sharma et al. (*42*) are wide area detectors (WADs) and point detectors such as inductive loops. The dynamic nature of dilemma zone detection makes point detectors less effective than those that track vehicles since they can only report the position of a vehicle at a specific point in space and time. One technique using one point detector uses the 85th and 15th percentile speeds from a historical speed distribution to determine the location for the point detector. The 85th percentile speed underestimates actual vehicle speeds and lowers the operational efficiency by increasing the average headway required for gap out.

The various detection schemes that use point detectors generally assume that the speed remains constant during the green phase; however, this assumption does not typically hold true in reality. The effect of a traffic signal as drivers get closer to the intersection is to increase the variance on the approach speeds. Since a WAD monitors vehicles continuously on the approach it can theoretically reduce or remove the speed variance. Instead of using extrapolated values as required by point detection systems, WADs measure the speed and position of vehicles over their detection range. This report establishes comparison metrics and attempts to quantify how well the selected WAD was able to monitor and protect vehicles approaching the dilemma zone on two high-speed intersection approaches at an instrumented intersection in Noblesville, Indiana. However, the report does not attempt to evaluate the proprietary algorithm embedded in the WAD.

Table 8 lists and describes the tests conducted compared to point detection. The table lists the following four values that are intended to reflect how well the WAD does its job:

- Accurately detect vehicle entry into the dilemma zone. The WAD should not have any false calls or missed detections of vehicles as they enter a certain location upstream of the stop line.

- Accurately track vehicle position. The WAD should precisely measure the position of each vehicle within the zone of interest.
- Accurately measure vehicle speed.
- Accurately detect vehicle departure from the zone of interest.

The first and fourth values (starts detecting vehicles and drops call) indicate the functional range of the WAD. The values should define fairly crisp boundaries, but some variation is acceptable. Once a vehicle has been tagged, the WAD must track it continuously through the detection zone. This research used a control volume test to evaluate the change in the number of vehicles within a control range. This metric was intended to determine false detections being generated or true detections being dropped before the vehicle clears the end of the detection area. There was also a volume comparison against inductive loops to determine excess or shortage in the number of vehicles detected over a long-term aggregation period. Finally, there was a probe vehicle test for accurate speed and position that used a sedan, a pickup truck, and an eight-passenger van, all equipped with a GPS handheld device to track the vehicle. Speeds obtained from the GPS devices were validated against the Onboard Diagnostic Device (OBD) in each vehicle.

Table 8. Comparison of Point Detection versus Wide Area Detection (*42*).

Performance Requirements	**Expected Capability**		**Test Conducted**
	Point Detector	**WAD**	
Accurately detect vehicles entering zone	Yes (Advance Detector)	Yes	Start distance histogram Control volume test Volume comparison against loops
Accurately track vehicle position	No	Yes	Probe vehicle test for accurate position
Accurately track vehicle speed	No	Yes	Probe vehicle test for accurate speed
Accurately drop calls when vehicle crosses stop line	Yes (Stop Line Detector)	Yes	End distance histogram Control volume test Volume comparison against loops

The research included ten runs through the intersection in each direction with each probe vehicle. Tests dynamically synchronized internal clocks between the data collection computer and GPS devices to a 0.01-sec precision. The research used a regression analysis to analyze the distance and speed errors. A summary of these results follows (*42*).

- Distance error analysis.
  - There was a systematic negative bias in the distance reported by the WAD in the southbound direction, but a fixed correction could remedy the problem.
  - The effect of distance, speed, and acceleration on the position accuracy was within 5 ft for the operating range, which was within the acceptable realm.
  - The vehicle type affected the estimation accuracy. Larger vehicles are reported to be further away than their actual distances.

- Speed error analysis.
    - Speed error was low in both directions.
    - None of the speed-error causes had a significant impact on the accuracy. The speed error was within 2 mph for the operating range.
- Call activation and deactivation performance.
    - There were 45 errors per day in one direction during the control volume tests, but the other direction was acceptable.
    - The volume comparison against loops indicated a mean error of 340 vehicles per hour (vph) in one direction and 180 vph in the other. Sources of these errors included simultaneous double detection of large vehicles, turning vehicles, and vehicles in the standing queue.
- Start distance and distance histogram.
    - Undesired detection of turning movements and multiple identification of the same vehicles resulted in higher than desired errors. Queue noise was less for shorter turn bays.

In conclusion, the structured approach used by Sharma et al. indicated that, although the WAD should have demonstrated superior dilemma zone protection when compared to point detectors, the results were mixed. The WAD performs reasonably well for vehicle tracking; the fixed bias can be removed by tweaking the setup parameters. For the four identified metrics, the authors offered the following summary:

- Accurately detect vehicle entry. Performance of the WAD was substandard due to excessive number of false detections generated by turning traffic and standing queues. It counted three to four undetected vehicles per hour.
- Accurately track vehicle position. WAD performance was good. The only problem was a fixed bias in one direction which could be removed by fine-tuning the sensor in the field.
- Accurately track vehicle speed. WAD performance was satisfactory. In a few cases, it did not update speeds beyond a point in time, particularly when adjacent vehicles were moving closely together.
- Accurately detect vehicle exit. Performance was seriously affected by turning traffic and standing queues.

In summary, the WAD showed potential for improving both the safety and efficiency of dilemma zone protection compared to point detectors. However, it needs improvement in its detection and tracking accuracy, particularly when used on approaches with significant turning traffic (*42*).

For evaluating vehicular detection systems at signalized intersections, Chitturi et al. reported on the design and implementation of a testbed for detector testing. The report included design of the hardware setup required for real-time monitoring of the sensors, programming the devices for data capture, and development of algorithms to automate the analysis of the recorded data. The authors described the different types of data required and how the hardware setup was used in the process. Timestamp and video data were the primary data collected to accomplish the study objectives. The process used video data to calibrate and validate the algorithms that analyze the timestamps and for verification of the preliminary results given by the computer algorithms. The video data was also useful for identifying possible causes and solutions for errors in vehicle detection performance (*43*).

The authors also presented the algorithms developed for the automated analysis, their calibration and validation. The initial data analysis used timestamp data to identify potential errors. This analysis required development, calibration, and validation of algorithms to quantify four commonly used performance measures (false calls, missed calls, stuck-on calls, and dropped calls). The process also required further analysis of the timestamps to address artifacts of video detection that may not be applicable to other detection technologies. In the final stage, the analysts performed manual verification on every potential error to ensure that the performance measures computed by the algorithms were correct. The authors noted that the testbed presented in the study can be used to evaluate any detection system at signalized intersections as well as free-flow conditions (*43*).

Hurwitz et al. investigated the impacts of using a Wavetronix SmartSensor Advance sensor to provide advanced vehicle detection and mitigation for dilemma zone incursions at high-speed signalized intersections (*44*). The authors identified a four-way fully-actuated high-speed signalized intersection in Clarendon, Vermont, for testing because the site had both the requisite safety related issues and infrastructure to allow for the successful implementation of the sensor. The sensor uses digital wave radar technology to provide continuous detection up to 500 ft away from the sensor head, in this case resulting in about 400 ft continuous detection back from the stop line.

In addition to the detections observed using point sensors and the radar sensor, the project collected eight hours of video under each test condition and made a direct comparison between the types and frequency of dilemma zone incursions during both conditions. The analysis used several different performance measures, relying on a Chi-square significance test to determine differences in detections. The Chi-square test showed that drivers experienced less difficulty deciding to stop or proceed under radar sensor control. The analysis ran another Chi-square statistical test to determine if the rate of Red-Light-Running (RLR) was statistically different between inductive loops compared to the radar sensor. The results showed that the rate of RLR for the radar detector was better but the difference was not statistically significant.

In research sponsored by the Texas Department of Transportation, Middleton et al. (*45*) found that TxDOT and other state departments of transportation as well as cities nationwide were using video detection successfully at signalized intersections. However, operational issues with video detection systems were occurring at some locations. The resulting issues varied but included:

- Camera contrast loss resulting in max-recall operation.
- Failure to detect vehicles leading to excessive delay and red-light violations.
- Degraded detection accuracy during nighttime hours.

This research resulted in the development of a formalized video detection test protocol and a set of performance measures that agencies can incorporate in future purchase orders and use to uniformly evaluate video detection products. It also resulted in the development of a video library and conceptual plans for a field laboratory for future projects to deploy a range of video detection products at an operational signalized intersection. Researchers evaluated alternative video stop line detection designs and developed methods for enhancing the operation of video detection through adjustments in controller settings for day versus night versus transition periods, zone placement, and camera placement. Another option for improving video detection but not included in Project 0-6030 is the use of thermal imagers instead of standard video cameras (*45*).

CHAPTER 3. FIELD DATA COLLECTION – RIVERSIDE

INTRODUCTION

In *Task 1 Develop Test Plan*, the research team proposed a list of detectors, general locations for tests, and the methodology of testing for consideration by TxDOT for this research project. As part of the Test Plan, the research team proposed what to test, where to test, and test metrics for collecting and analyzing data. This plan, once approved by the PMC, provided the basic foundation for the remainder of the project. Determining what to test came primarily from the extensive literature search and research team experience, but again, it was approved by the PMC. The research team initially offered some potential locations for testing based on their near proximity to TTI headquarters to minimize travel time and costs.

TEST PLAN

The test plan involved initial tests at the Texas A&M University's Riverside campus (a decommissioned air base now owned by the university) followed by tests at real-world intersections operated by the Texas Department of Transportation. The Riverside campus' controlled conditions offered an excellent opportunity to isolate variables affecting the performance attributes of detectors. Testing at Riverside included a variety of vehicle types and speeds that range from 50 mph to 70 mph. The runway length at Riverside is sufficient to accelerate a Class 8 truck-tractor to 70 mph before passing through the field of detection of about 1,000 ft.

The test plan involved vehicles traveling individually through the 1,000-ft intersection approach at constant speed. Other vehicles included in Riverside tests were a motorcycle, a sedan, and a pickup truck. One reason for including the large truck was to test the features that the Wavetronix Advance Extended Range offers specifically for large vehicles. After testing for a short time at Riverside, the research team discovered that the Riverside testing environment (with few vehicles) was inappropriate for evaluating the Advance's ability to classify vehicles by truck/non-truck, leading to a decision to postpone the test and conduct it at the intersections.

At the most basic level, the Riverside tests evaluated the accuracy of the estimated speeds generated by each detector and, where appropriate, the distances at which vehicles were detected as they approached the stop line. Secondly, these tests evaluated the application of these distances and speeds to predict each vehicle's trajectory and arrival in the dilemma zone. Continuous verification of speed and distance values was required to check the Wavetronix SmartSensor Advance and the Iteris hybrid detector. Comparing point detections by the Aldis GridSmart, Trafficware Pods, FLIR/Traficon video, and Wavetronix Matrix emphasized presence detection. Detectors communicated detection timestamps (ons and offs) to a NEMA TS-2 controller monitored by a laptop computer.

What to Test

Table 9 shows the final list of detectors included in lab/field tests. The PMC removed two other potential detectors that were initially considered. The longer term selection process also considered that initial tests at the Texas A&M University Riverside campus might reduce the list even further to ensure best use of available resources, especially given the limited time for completing the study.

Table 9. Detectors Included in TAMU Riverside Field Test.

System	Detector	Stop Line	DZ Detection	Technology
1	Aldis GridSmart	Primary	Secondary	Video
2	FLIR VIP w/IR Camera	Primary	Secondary	IR Video
3	Iteris Vantage Vector	Primary	Primary	Radar/Video
4	Trafficware Pods	Primary	Secondary	Magnetometer
5	Wavetronix SS Advance (SS-200E)	N/A	Primary	Radar
6	Wavetronix SS Matrix	Primary	N/A	Radar

The list of detectors in Table 9 includes six different detectors using the following technologies: video, radar, and magnetic (magnetometers). The Aldis GridSmart system involves an innovative concept using a single fisheye camera for stop line control, and it now offers optional rectilinear cameras for upstream detection if desired. These rectilinear cameras are included in this research.

One of the detection systems in Table 9, the Iteris Vantage Vector, uses a combination of technologies: radar and video. This hybrid detector uses Doppler radar for indecision zone/ dilemma zone protection and video for stop line detection. Another hybrid detector, the FLIR TrafiRadar, was initially included in these tests as well, but due to several issues with its setup it was removed from further testing. Trafficware Pods are wireless magnetometers that serve as point detectors but can also be grouped to replicate a long inductive loop. The FLIR (Traficon) video system uses an infrared imager to detect traffic. The final two detectors are radar detectors from Wavetronix. The Wavetronix SmartSensor Advance, SS-200E "Extended Range," is designed specifically for detection of vehicles in the dilemma zone. The Extended Range unit places emphasis on truck detections with its range being greater than that of the original Advance. The SmartSensor Matrix is designed for detection only at the stop line.

Where to Test

The research team began testing at the Texas A&M Riverside campus to identify and solve as many issues as possible before moving to TxDOT intersections with real-world traffic. For identifying potential intersection locations, TTI relied on both TxDOT district personnel and equipment distributors. Complete information on the intersections selected and pertinent factors are provided in Chapter 3.

Test Metrics

For testing at the stop line, the analysis will use the following measures:

- False calls, including:
    - Calls received when no vehicle is present.
    - Calls received when a vehicle is present in the adjacent lane but not in the observed lane.
    - Multiple calls received due to flickering when only one vehicle is present.
- Missed calls, including:
    - Vehicles passing between two monitored lanes.
    - Vehicles passing directly through the detection zone.
- Stuck-on calls (i.e., calls that do not end when the vehicle leaves the detection zone).
- Dropped calls (i.e., calls that end while the vehicle is still present in the detection zone).

For testing the Wavetronix SmartSensor Advance, which is a tracking detector, the research team developed a process to test the following metrics:

- Accurately detect all vehicles entering the dilemma zone. The detector should not have any false calls or missed detections of vehicles as they enter a certain location upstream of the stop line.
- Accurately track vehicle position. The test detector should precisely measure the position of each vehicle within the zone.
- Accurately measure vehicle speed.
- Accurately detect vehicle departure from the zone.

METHODOLOGY

The methodology covered in this Research Report includes both Riverside controlled environment data collection and data collection at TxDOT intersections. Appendix A provides more details on activities at Riverside. Both Riverside activities and intersection activities involved the four steps listed below. The organization of this report keeps the first three components together and places the data analysis at the end to transition to the detector guidelines.

- Install equipment.
- Verify equipment operation.
- Collect and compile data.
- Analyze data.

Install Equipment

Table 10 provides the list of tests that the research team determined would be feasible for each of the selected detectors. This list is partially a function of what each detector makes available through its output and partially by what happens when a detection event occurs. All detector actuations came to the controller in the cabinet and were stored on a laptop computer in the form of timestamps. Having a single source of clock time was essential to minimize the impact of possible clock drift. Tests at the stop line were yes/no and detection start/stop values. Tests upstream varied by detector but were still stored in the laptop as timestamps. The Aldis GridSmart and FLIR VIP upstream detection involved detection yes/no and start/stop values. The Iteris Vantage Vector and Wavetronix Advance both used Doppler radar for upstream detection so the research team developed a special procedure (described later) to test their accuracy. The Trafficware Pods are simple presence detectors positioned at known locations and spaced 100 ft apart along the approach but otherwise were evaluated similar to stop line detectors. Again, their evaluation used timestamps.

Other variables that deserved consideration while conducting these tests include the effects of weather and light conditions, vehicle speed, vehicle type, and vehicle spacing. Vehicle spacing could be a variable as well, but the Riverside tests were planned as single vehicle tests with only one vehicle detected at a time. Finally, controller settings could vary, but the test plan considered controller settings at subsequent intersection tests.

Table 11 summarizes the desirable factors to be included in the Riverside tests, although some of these factors (e.g., fog or other weather factors) were not available during planned tests.

Table 10. Desired Detector Tests.

Detection System	Test Upstream	Test at Stop Line
1.Aldis GridSmart	Vehicle detected: yes/no When detection begins When detection ends	Vehicle detected: yes/no Stop line call starts Stop line call ends
2. FLIR VIP w/IR camera	Vehicle detected: yes/no When detection begins When detection ends Compare against optical camera	Vehicle detected: yes/no Stop line call starts Stop line call ends
3. Iteris Vantage Vector	Vehicle detected: yes/no Tripwire detection TL1, TL2 Tripwire detection TL1, TL2 DZ prediction accuracy	Vehicle detected: yes/no Stop line call starts Stop line call ends
4. Trafficware Pods	Vehicle detected: yes/no Where detection begins Where detection ends	Vehicle detected: yes/no Stop line call starts Stop line call ends
5. Wavetronix SS Advance (SS-200E)	Vehicle detected: yes/no Where detection begins Where detection ends Tracking accuracy (position) DZ prediction accuracy Vehicle class (truck/non-truck)	N/A
6. Wavetronix SS Matrix	N/A	Vehicle detected: yes/no Stop line call starts Stop line call ends

Table 11. Desired Conditions for Detector Tests.

Variable	Condition
Weather factors	Sunny and dry Rain Fog
Lighting factors	Day Night Transitions Shadows
Vehicle speeds	50 mph 70 mph
Vehicle types	Motorcycle Sedan Sport Utility Vehicle Pick-up truck Truck-tractor

The research team spent considerable effort in early communications with all equipment vendors to discuss project objectives and work out details pertaining to acquiring equipment for tests. The actual requests and initial discussions started in early October 2014. On November 10, 2014, TTI moved a NEMA TS-2 cabinet from its lab in the Gibb Gilchrist building on the Texas A&M University campus to runway 35C (a north-south runway) at the Riverside campus. Figure 24 shows that the Riverside campus is near the intersection of Highways 21 and 47. The figure also shows runway 35C where the major testing reported in this document occurred. This runway has sufficient length to accommodate all vehicles included in the tests at speeds up to 70 mph, including the Class 8 Freightliner truck. Figure 25 is a recent photo of the equipment cabinet and the detectors installed for testing.

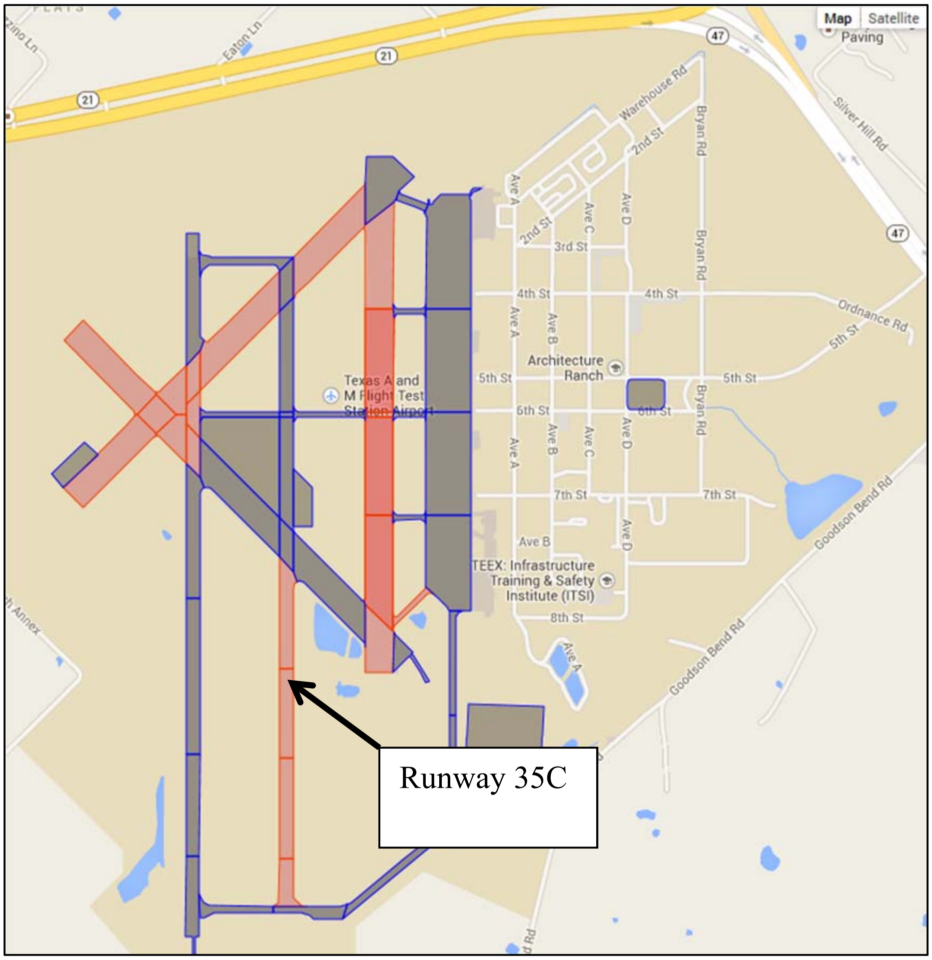


Figure 24. TAMU Riverside Campus.

Figure 26 represents a plan view of runway 35C and the position of the nine wireless Pods used for this project. One Pod is positioned at the stop line, and the other eight Pods are positioned along the test lane at 100-ft intervals. The flow of traffic in this figure is from right to left (southbound). The Riverside tests included the noted range tests as well as detection characteristics of each detection system.

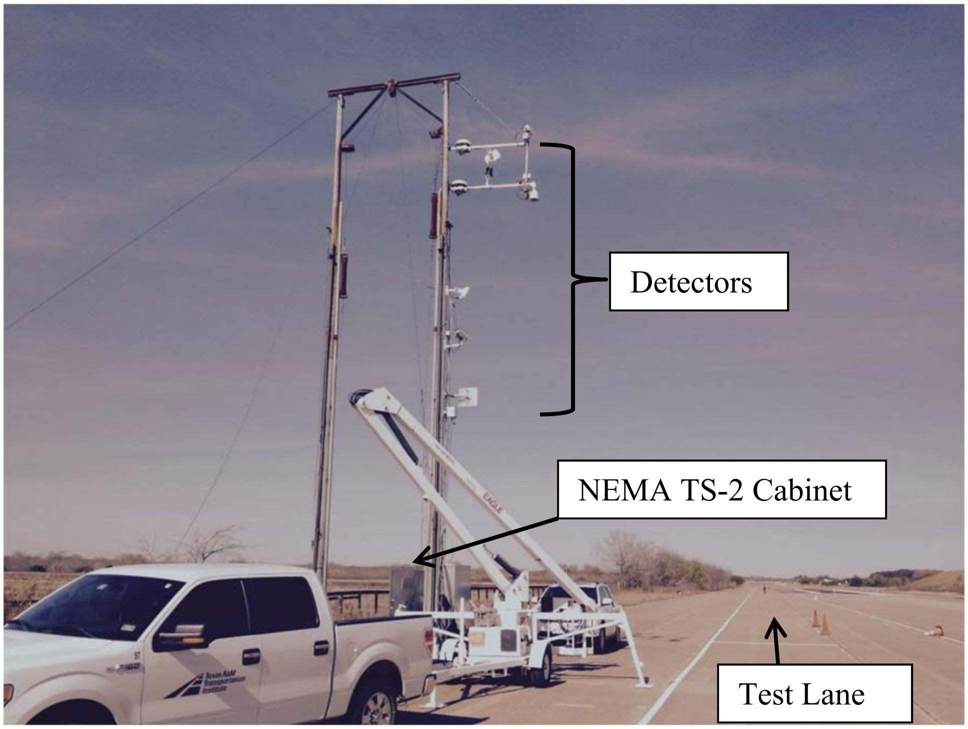


Figure 25. Photo of Test Site on Runway 35C Facing North.

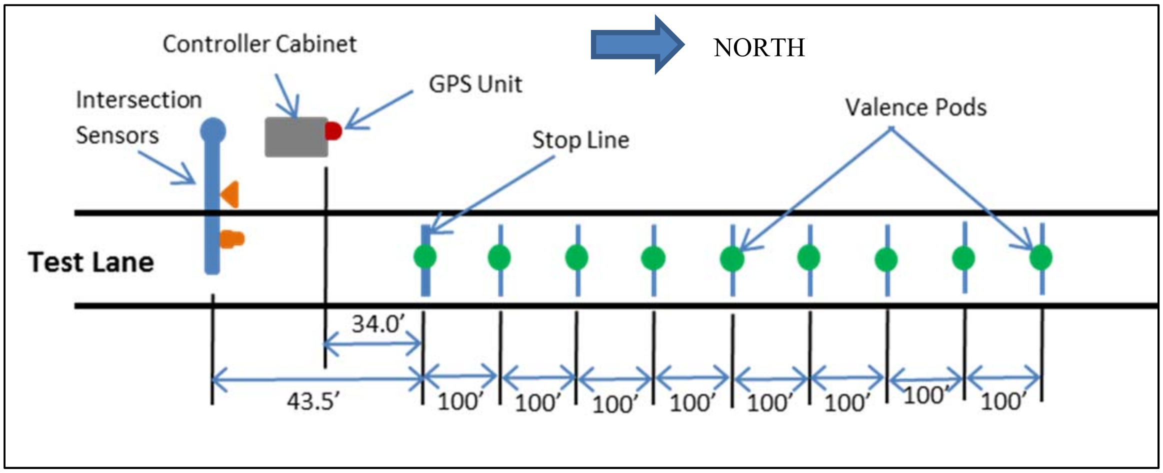


Figure 26. Plan View of Runway 35C and Cabinet Placement.

Early in the equipment preparation process, the research team investigated potential ways to collect and store data from all systems simultaneously. Methods that used multiple sources of timestamps were problematic from the standpoint of synchronizing activities following the data collection process. The TTI team developed custom applications to collect the data needed to evaluate the sensors included in this project. In order to eliminate the time synchronization problem between the event data collected by the applications, the TTI team used a single field laptop to run all the applications. The applications used the system clock of the laptop to timestamp events collected by each application, and consequently all of the event data collected used the same time reference.

The TTI-owned NEMA TS-2 cabinet is equipped with four Bus Interface Units (BIUs) and 64 channels for connecting the suite of test detectors. Table 12 lists the channels used and the detectors that communicate with each channel. Channels 1 and 3 originally received input from the FLIR TrafiRadar hybrid detector, but as noted elsewhere, this detector did not perform as expected and continued testing was deemed premature. Having 64 channels available for use added flexibility and variety in the way data could be routed from the suite of detectors. Assigning detectors to specific BIUs helped the research team manage the 16 data streams that were received by the controller.

Table 12. Detector BIU Channel Mapping in TS-2 Cabinet.

BIU #	Channel	System	Detection Location
1	5	FLIR	Traficon VIP w/IR cam - stop line
	13	Iteris	Iteris stop line
	15	Iteris	Iteris tripline at 485 ft
	16	Iteris	Iteris tripline at 566 ft
2	17	Wavetronix	Matrix stop line
	21	Wavetronix	Advance (SS-200E, upstream)
3	38	Aldis upstream camera	Video camera, upstream
	46	Aldis fisheye camera	Stop line
4	51	Trafficware Pod	100 ft from stop line
	52	Trafficware Pod	200 ft from stop line
	53	Trafficware Pod	300 ft from stop line
	54	Trafficware Pod	400 ft from stop line
	55	Trafficware Pod	500 ft from stop line
	56	Trafficware Pod	600 ft from stop line
	57	Trafficware Pod	700 ft from stop line
	58	Trafficware Pod	800 ft from stop line
	59	Trafficware Pod	Stop line

Specific challenges to testing the selected detectors included how to test multiple detectors that track vehicles along the approach and predict vehicle trajectories approaching the dilemma zone. While point detection might be a useful tool to check the distance of vehicles and perhaps speeds, it would not easily allow for checking detectors that generate continuous distance and speed values on each vehicle along the approach. Therefore, TTI developed two methods—one using a global positioning system (GPS) unit mounted in a probe vehicle and the other using point detectors. The GPS method communicated with the intersection by radio mounted in the probe vehicle. The second method used Trafficware Pods positioned precisely at 100-ft intervals along the runway to indicate vehicle positions. This procedure determined vehicle locations between Pods by interpolation since speeds were constant. Subsequent data analysis indicated which method was more appropriate for comparison with each test detector.

The GPS procedure used a TTI-owned Toyota Highlander equipped with a high-end Trimble GPS device as a vehicle probe proceeding toward the intersection. The GPS device was connected to an Encomm 5200 radio that broadcasted the RMC (recommended minimum specific Global Navigation Satellite System Data[1]) sentence received from the GPS unit every 100 milliseconds.

The second component in this system was a laptop computer at the intersection that could receive the GPS messages sent by the TTI Highlander using the Encomm 5200 radio. The TTI program also received standard messages from a second GPS unit installed at the intersection. Each time the program received a GPS message from the Highlander, it used the local latitude/longitude from the intersection GPS unit to calculate the distance of the vehicle from the intersection. It logged the distance with a timestamp (local system time) to a file at the same 100 millisecond rate. Figure 27 indicates the orientation and lateral dimensions used by the Highlander in these field tests. Figure 28 indicates the longitudinal measurements, showing the distances measured between the two GPS units and corrected to reflect the distance parallel to the test lane (as indicated by “Calculated Distance”).

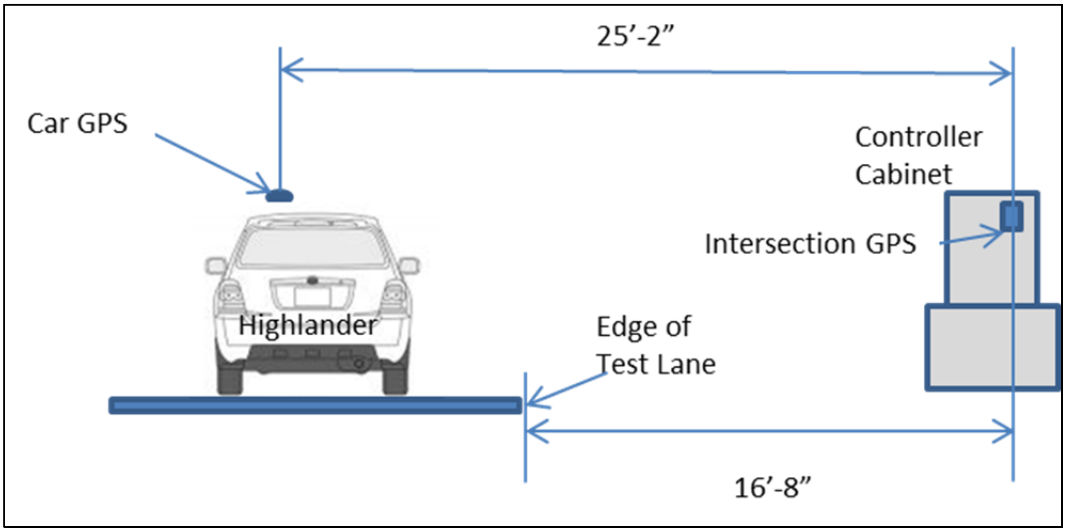


Figure 27. Lateral Dimensions Used for GPS.

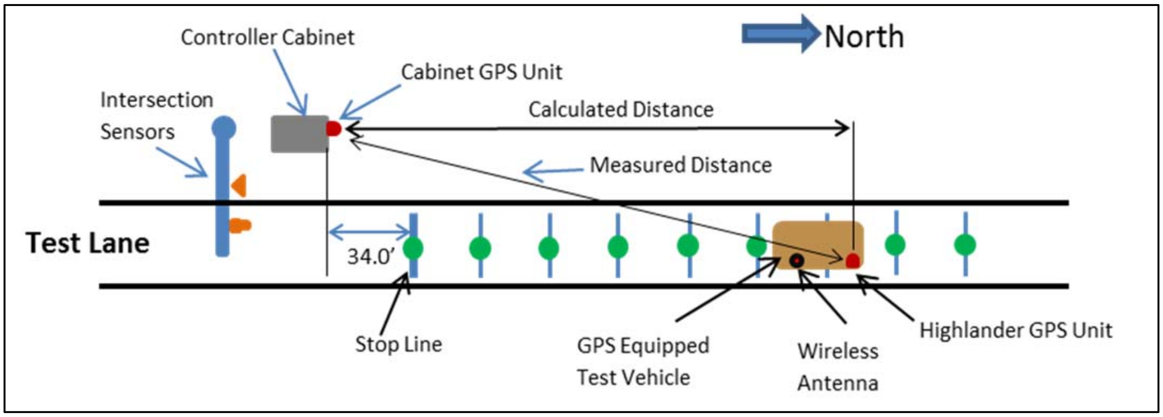


Figure 28. Longitudinal Dimensions Used for GPS.

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[1] RMC is specified in the National Marine Electronics Association (NMEA) standard.

The two applications that operated simultaneously on the field laptop were:

- A TTI-developed application called “NTCIP Portable Traffic Signal Evaluation System” (NPTSES_M), which communicated in real-time with the controller using the NTCIP 1202 messages and logged in real-time (every 30 to 50 milliseconds) the detector actuations. NTCIP is National Transportation Communication for ITS Protocol.
- A TTI-developed application that used the car GPS location information and a stationary GPS device at the intersection to track the location and distance of the vehicle from the stop-line while it travelled through the detection zone.

The first program captured detector actuations in real time from the various detection systems being evaluated. The second software module captured the GPS coordinates of the Toyota Highlander to calculate its distance from the stop line while traveling in the detection zone of the sensors.

Subsequent processing fused data in the two files to determine the speed, distance, and timestamp of the vehicle upon detection by each sensor. The same procedure recorded the timestamp and distance when detection ended. The On and Off actuations of each detection system serve as a verification mechanism to validate the performance of each system in extending the phase for protecting the dilemma zone. For detectors that continuously monitor the speed and distance of approaching vehicles (e.g., Doppler radar), there is a need to track each vehicle using, in this case, GPS to verify detector output data. This verification compared the distance from the intersection stop line where the vehicle was detected and the duration of the detector call as measured by the TTI data collection to the dilemma zone boundaries configured in each system.

Data file post-processing automatically integrated the detector output files that include the detector actuations (On/Off) timestamps with the GPS data files that include the vehicle distance. Since the files ran on the same laptop and used the laptop system time as the timestamp for records logged into the files, subsequent analysis could sort the data based on time. Subsequent tweaks to the process considered the GPS message transmittal delay and other sources of delay. GPS also generated accurate speeds to be compared to speed estimates from test detectors. Figure 29 illustrates this data collection processing.

Verify Equipment Operation

Cabinet and Detectors

Starting with the NEMA TS-2 cabinet, researchers began to meticulously check each component of the detection and monitoring setup to ensure accuracy and reliability. As in the initial setup process, some operational issues arose that were not anticipated and required changes in positions of sensors or changes in how the research data were collected. For example, the TrafiRadar and FLIR camera systems mounted at 35 ft above the ground were unable to cover sufficient runway length from that height due to the camera optics. The research team subsequently lowered them to a height of 23 ft above ground. Even then, the FLIR IR camera only covered about 150 ft upstream of the stop line. The manufacturer also asked the researchers to change out the original TrafiRadar detector because it too had suboptimal optics. The research team complied with this request.

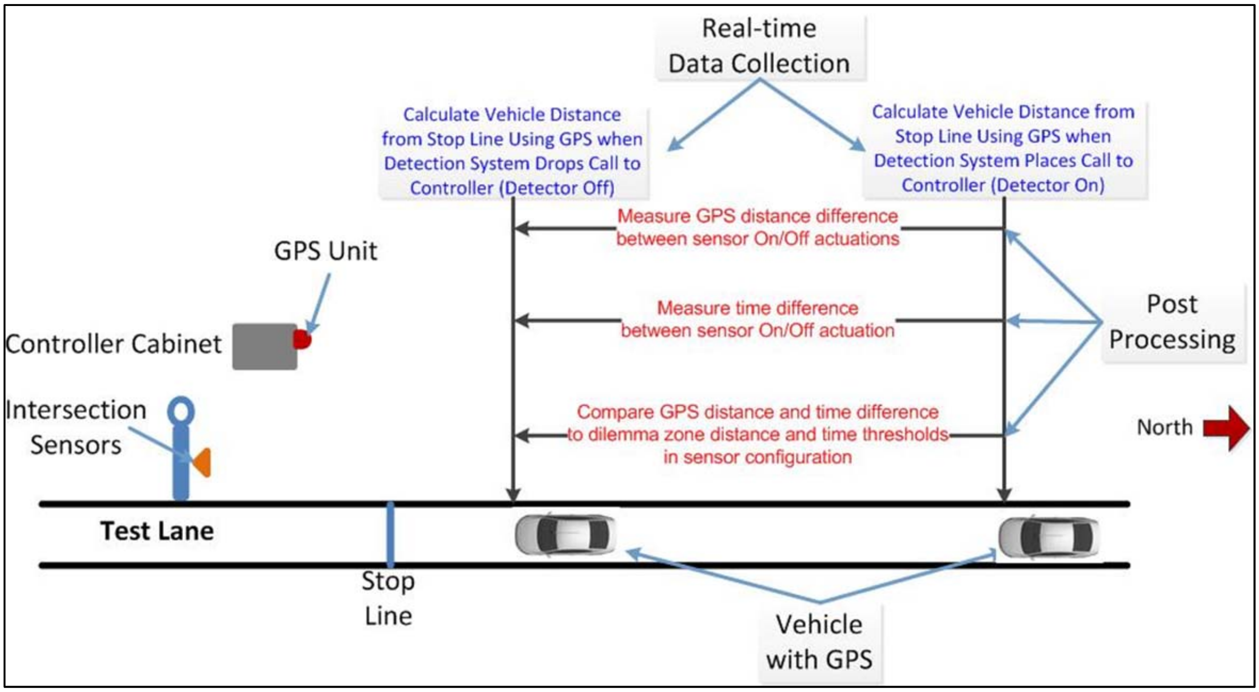


Figure 29. Data Collection Process for GPS and Detectors.

The overall plan for conducting these Riverside tests involved testing all detectors simultaneously to overcome any potential differences in weather and light conditions from one test period to another. However, as desirable as that might be, the simultaneous test scenario resulted in a potential problem with multiple radar units operating in close proximity. The four detectors that incorporate radar technology are: Wavetronix SmartSensor Matrix, Wavetronix SmartSensor Advance, FLIR TrafiRadar, and Iteris Vantage Vector. The last two are hybrids and use video detection as well as radar. The research team ran tests during January 2015 that suggested interference between some of the four radar units operating simultaneously in close proximity to each other. The researchers conducted several series of test runs on January 27, 2015, at the desired speed range, finding that four runs out of 30 (13 percent) generated anomalous results. Even though this result did not conclusively prove that any of the radar results were compromised by interference, the team decided to run each radar unit separately anyway to mitigate potential TxDOT and detector manufacturer concerns. That required the research team to run each set of conditions repeatedly instead of running all radars individually, with the exception of the two Wavetronix detectors, which were designed to be operated together.

GPS Verification

Preparing the GPS process required finding the proper car-mounted radio with the needed range to communicate over a distance of at least 1,000 ft. The system also needed a fixed antenna at the cabinet so field personnel installed one on top of the cabinet. Once the car GPS and radio were working in harmony with each other and with the second GPS unit at the cabinet, the research team made several test runs along the runway to check the stability of the system and the accuracy of distances measured.

During the GPS verification activity, TTI tested the ons and offs generated by the Trafficware Pods as a preliminary test of the GPS components. This activity followed the development of the

GPS program discussed beginning page 51 to compute the distance from the stop line to the GPS vehicle. Results from this activity indicated that both the GPS and the Pod characteristics needed to be better understood before making a comparison. The research team decided to develop correction factors to improve on the prediction of spatial positions estimated by the GPS. This report provides information on that process.

To expedite reading and analyzing the raw data files, the TTI team developed a macro for Microsoft Excel© to run both the detector data and the GPS data. During data collection, the GPS units result in one file being generated at the same time that detectors are running. Test runs generated the following data for each detector channel:

- Time of call received (on).
- Speed of vehicle when call received.
- Distance from stop line of vehicle when call received (corrected for site dimensions, vehicle dimensions, and the GPS receiver's position in the vehicle).
- Travel time to stop line when call received.
- Time of call dropped (off).
- Speed of vehicle when call dropped.
- Distance from stop line of vehicle when call dropped (corrected for site dimensions, vehicle dimensions, and the GPS receiver's position in the vehicle).
- Detector presence time.

Detector Verification

Table 13 summarizes the interpretation of timestamps for each detector. The TTI-developed application, NPTSES_M, got the detector status from the traffic signal controller every 30 to 50 milliseconds using NTCIP 1202 *vehicleDetectorStatusGroupActive* commands. Any time the application detected a change in the status of any one of the monitored detectors either to On or Off, the application logged the change in status with a timestamp into a daily log file. This timestamp (Time On) in Table 13 is used by the detectors in different ways. Some detectors simply use the Time On as the front of the vehicle and the detector interprets that signal as the beginning of presence detection and nothing more. The presence of that vehicle ends when the detector returns to its baseline state by registering a Time Off. Detectors that only detect presence are:

- Aldis GridSmart.
- FLIR VIP with IR camera.
- Trafficware Pods.
- Wavetronix SmartSensor Matrix.

Upstream Radar Detector Verification. Other detectors in the list do more than sense presence of a vehicle. They detect the front of each vehicle and immediately begin to process the movement of the vehicle in terms of speed and distance from the detector. Each of these detectors utilizes Doppler radar reaching upstream as far as about 900 ft from the sensor to first assign a unique identifier to each detected vehicle, then tracks each vehicle as it progresses toward the intersection at a frequency of about 100 milliseconds. The three detectors originally included in this research that used Doppler radar to track vehicles starting at 600 to 900 ft were:

- FLIR TrafiRadar.
- Iteris Vantage Vector.
- Wavetronix SmartSensor Advance (SS-200E).

Table 13. Interpretation of Timestamps.

Detection System	Time On	Time Off	Value(s) Measured
1.Aldis GridSmart			
a. Upstream	Point detection	Point detection	Vehicle presence
b. Near Stop Line	Point detection	Point detection	Vehicle presence
2. FLIR VIP w/IR cam.			
a. Upstream	Point detection	Point detection	Vehicle presence
b. Near Stop Line	Point detection	Point detection	Vehicle presence
3. Iteris Vantage Vector			
a. Upstream	TL1, TL2 On	TL1, TL2 Off	Distance & Extension
b. Near Stop Line	Vehicle entry	Vehicle exit	Vehicle presence
4.Trafficware Pods			
a. Upstream	Point detection	Point detection	Vehicle presence
b. Near Stop Line	Point detection	Point detection	Vehicle presence
5.Wavetronix SS Advance			
a. Upstream	Vehicle entry	Vehicle exit	Distance & speed
b. Near Stop Line	N/A	N/A	N/A
6.Wavetronix SS Matrix			
a. Upstream	N/A	N/A	N/A
b. Near Stop Line	Vehicle entry	Vehicle exit	Vehicle presence

At the beginning of this research project, the first two detectors used a procedure similar to one that had previously been patented by Wavetronix. As this research project continued its testing at the Riverside campus, a lawsuit required Iteris to stop manufacturing and using its similar firmware. The FLIR TrafiRadar detector's future was also in jeopardy for the same reason. Iteris had already developed a secondary method of dilemma zone protection using two triplines (shown as TL# in the table), so TTI's testing of that device shifted to evaluating the tripline mode and away from the original continuous mode. At about that same time, the research team recommended removing the FLIR TrafiRadar from further consideration due to many delays. The TxDOT Project Management Committee agreed that removing it was appropriate.

The output from the Iteris Vantage Vector are twofold—one output is generated by the radar unit as a vehicle approaches and passes through each trip line and the other output is generated by the video camera. For the radar operation, the user inputs an extension time for each tripline based on the radar-measured vehicle speed. A vehicle traveling at a speed below the set threshold speed should not result in an extension being sent to the controller. There is also a presence time inherent with each trip line that will be covered later in this document. In Table 13 the Time On and Time Off for the upstream detection by the Iteris detector was recorded to indicate tripline detections and extensions.

The Wavetronix SmartSensor Advance only uses Doppler radar and only covers the upstream area. Therefore, the data collection plan only records an upstream on and off to be recorded at the controller for this detector. The Advance uses a unique patented process for predicting vehicle arrival in the indecision zone called time of arrival. It continuously measures vehicle-specific speed and vehicle distance from the stop line and, based on these two continuously updated measurements, predicts vehicle arrivals in the indecision zone. The installer inputs travel time values through a PC interface (e.g., 2.5 to 5.5 sec for non-trucks) to define the indecision zone.

One of the issues discovered early in testing the four radar detectors simultaneously in close proximity at Riverside was possible interference. In other words, one radar unit might be receiving, or adversely affected by, signals generated by another radar unit. There were no obvious indications of such interference, but testing each detector separately removed the possibility for doubt. The research team chose to operate each radar detector independently with only one radar unit operating at any given time. The exception was the two detectors from Wavetronix, which were designed to be operated in close proximity with no interference issues.

As noted elsewhere, during the Riverside tests Iteris changed to a tripline detection mode, requiring the research team to reevaluate its test method and re-collect the data. Instead of monitoring the continuous mode, TTI began evaluating vehicle detection at triplines and the vehicle extensions generated by the Vantage Vector. The initial settings involved a 2.5-sec and a 3.0-sec extension with triplines set at the following distances:

- Channel 15: Near tripline at 485 ft for vehicles traveling at or above 45 mph.
- Channel 16: Far tripline at 566 ft for vehicles traveling at or above 65 mph.

At speeds at or above 65 mph, vehicles should cause detections at both triplines, but speeds below 65 mph (but at or above 45 mph) should only trigger the near tripline at 485 ft. Therefore, the higher Riverside test speed of 70 mph should always generate two calls—one at about 566 ft followed by another at about 485 ft. By the time the research team began testing at signalized intersections in Austin and Houston, Iteris had changed its firmware to utilize three triplines instead of two.

Trafficware Pod Verification. Early testing of the Trafficware Pods indicated that the system was robust, stable, and accurate for most vehicle types. However, its operating characteristics were not well known and needed further evaluation. The researchers devised a field experiment to better understand its detection characteristics and to determine whether its use as a possible ground truth source might be expanded. The experiment started by using two Class II piezoelectric sensors to capture axle actuations with data stored on a Jamar vehicle counter. The resulting data were not useful due to clock drift in the classifier. The following more intense and time-consuming activity involved using tapeswitches connected to a laptop PC running a LabView© program written specifically by the research team for this purpose.

The research team spent two days collecting tapeswitch data at Riverside to define magnetometer ons and offs (activations and deactivations), with the Trafficware system being the only one monitored in the cabinet. The tests used three magnetometers spaced 30 ft apart along with tapeswitches positioned 1 ft past each Pod. Pod #1 was the first encountered by each vehicle, followed by Pod #2 and then Pod #3. Vehicles used on the first day were as follows:

- Ford F-150 (1/2 ton pickup).
- Dodge Minivan.
- Toyota Highlander.

On the second day, Pods were in the same order as the previous day, but speeds were 50 mph and 70 mph. Vehicles used on this date were:

- Freightliner Class 8 truck tractor.
- Ford F-250 (four-wheel drive pickup).
- Ford Fusion (sedan).

The tapeswitch data collection effort was beneficial for two reasons: 1) to better define the activation/deactivation characteristics of the Trafficware Pods, and 2) to use the on/off characteristics to verify locations of vehicles approaching the intersection stop line. All speeds at Riverside were constant so vehicle location could be verified not only every 100 ft at Pod locations but at intermediate points as well through interpolation.

TTI assembled the observations for the six vehicles into one master file and imported it into SAS©, and then ran some summary statistics for speeds of 50 mph and 70 mph. Findings indicate that there is no significant difference between vehicles, so the same correction factor could be applied to all vehicles. Considering only time delay (but not distance delay), the pods performed about the same for 50 and 70 mph. Specifically, they give a 0.24-sec delay for the on time and the same delay for the off time, with a standard deviation of 0.075 sec. The distance delays are different across the speeds as expected.

TTI then corrected its Excel spreadsheet and moved forward with correction factors of 0.24 sec for on times and 0.24 sec for off times. Having one correction factor for on and another for off, instead of having to use separate factors for each combination of speed, vehicle, and detector status (on/off) facilitated quicker change to the spreadsheet process.

One final verification activity that was considered a subset of the tapeswitch tests was the use of a high-speed video camera positioned near the cabinet on the test runway at Riverside with one Trafficware Pod centered in the camera view. This test mounted the high-speed camera at right angles to the travel direction and about 10 ft from the near lane edge, so the position of the vehicle in relation to the Pod was recorded every millisecond for a period of 4.0 sec. Test runs used the Highlander at 50 mph and 70 mph. Test results clearly verified the results from the tapeswitches. Appendix B contains more details on the results.

Collect and Compile Data

The initial contacts to procure the data collection equipment began in October 2014. TTI moved a NEMA TS-2 controller cabinet to the field site at Riverside on November 10, 2014, and continued installing and setting up the test site. The final equipment to arrive at TTI headquarters was from Trafficware on December 23, 2014. After the Christmas break, TTI installed the Trafficware equipment on January 6, 2015. Detector manufacturers were encouraged to check each system to ensure optimum performance. The research team allowed modifications to firmware or reorientation of detectors until the manufacturers' representatives were satisfied. Early testing resulted in discarding data due to various factors until the first useable Riverside data collection occurred on February 9, 2015.

Once installation and validation of all test detectors was complete and initial issues resolved, the research team began collecting data using a process of constant speeds (50 mph and 70 mph) and one vehicle in the detection zone at a time. Several issues still arose as indicated elsewhere in this document but all were resolved and testing resumed. Data collection and storage occurred on-site as data collection transpired followed by data compilation in the office using a standardized process. Data analysis resulted in a variety of graphics and descriptive statistics to fully explain research findings and set the stage for developing future deliverables. Data collection at Riverside continued through late June 2015.

During the data compiling portion of this research, analysts were mindful of potential sources of discrepancies that could affect the results. For example, sampling rates lower than desirable were a source of error, but the analysis portion of the study used known methods to minimize their impact. Differences of a few milliseconds might be considered negligible from a practical standpoint, but the more rigorous research setting must rely on solid scientific methods and has to consider all discrepancies.

To verify the configuration, performance, and operation of the various detection systems selected for Project 0-6828, the TTI team used a suite of programs for real-time data collection. Due to the nature of the data collection system and the devices that were used, several sources could lead to discrepancy between the sensor measurements and the data collection measurements. These sources of discrepancy include:

- The GPS system used in the Toyota Highlander, while a high-end unit that outputs vehicle position every 100 milliseconds, could introduce small errors in the resulting estimated distances.
- Most of the sensors used have a cycle length of about 100 milliseconds. Any event that happens outside the boundaries of the cycle of each system, such as just before the cycle starts or just after the cycle ends, would lead to a discrepancy approaching 100 milliseconds in the detection of an event. For example, the Wavetronix SmartSensor Advance updates every 100 milliseconds and determines dilemma zone incursions. Any vehicle that is within the boundaries of the dilemma zone thresholds entered by the user and arrives just after the sensor cycle ends will not be detected until the next cycle of the sensor. However, since vehicle arrival is random, most of these detection discrepancies will be a few milliseconds on average.
- Similarly, the data collection software modules developed by TTI are running on a laptop running Windows 7, and they have data collection cycles that are between 30 and 50 milliseconds. However, the same phenomena can still occur as described above.
- The Trimble GPS used in the Toyota Highlander vehicle transmits the GPS coordinates of the vehicle to the laptop PC stationed near the stop line ten times a second.
- The Trafficware Pods use wireless communication to transmit their detection information to the base station in the cabinet. Wireless communication involves latency that must be accounted for. According to a Trafficware representative, the detection latency at the controller should be 10 milliseconds.

These sources of discrepancy could lead to total discrepancies in the range of zero to 200 milliseconds between an event detected by the data collection systems and the actual events. At 70 mph speeds, these differences might lead to a maximum spatial error in the range of plus or minus 20 ft. The methodology had to account for these discrepancies, so the research team investigated all potential error sources and established methodologies to mitigate their impacts.

During all data collection at Riverside, the research team always included a vehicle with the Trimble GPS unit running continuously so that the position and speed of one vehicle could be tracked at all times. As data were compiled for all vehicles and all detectors, the data storage procedure also included the GPS data for later analysis. Therefore, the project accumulated a wealth of data from this source even if it only applied to one vehicle. Table 14 summarizes the number of runs by weather condition (clear day, clear night, and rain day) and by speed (50 mph and 70 mph) that became available for further analysis. Results from these GPS runs are useful to supplement other data for all vehicles provided in Chapter 5.

Table 14. Number of Valid GPS Runs by Speed and Condition.

Detector Channel	**50 mph**			**70 mph**		
	Clear Day	**Clear Night**	**Rain Day**	**Clear Day**	**Clear Night**	**Rain Day**
FLIR IR VIP Video [SB5]	94	25	23	28	34	23
Iteris Vector Stop [SB13]	53	24	10	31	9	0
Iteris Vector Trip 485 [SB15]	53	24	13	34	10	8
Iteris Vector Trip 566 [SB16]	0	0	0	14	0	7
Wavetronix Matrix [SB17]	42	0	10	19	15	8
Wavetronix Advance [SB21]	42	0	10	20	16	10
Aldis Up [SB38]	149	33	24	66	36	23
Aldis Stop [SB46]	145	33	24	66	35	23
Pod at Stop Line [SB59]	152	34	24	72	34	22
Pod at 100 ft from Stop [SB51]	154	33	24	72	35	23
Pod at 200 ft from Stop [SB52]	153	33	23	72	35	23
Pod at 300 ft from Stop [SB53]	151	33	24	72	36	23
Pod at 400 ft from Stop [SB54]	151	34	24	71	36	23
Pod at 500 ft from Stop [SB55]	146	31	24	71	35	23
Pod at 600 ft from Stop [SB56]	145	30	24	68	35	23
Pod at 700 ft from Stop [SB57]	143	29	23	70	35	23
Pod at 800 ft from Stop [SB58]	136	22	23	70	36	23

CHAPTER 4. FIELD DATA COLLECTION – INTERSECTIONS

INTRODUCTION

The methodology used by the research team for signalized intersection data collection involved the same four major activities as earlier data collection at Riverside with the exception of the initial step of identifying the sites to use. As before with Riverside data, the analysis portion comes at the end of this document. The reader is cautioned that data collection and analysis reported in this chapter were severely constrained by the project schedule. This issue is addressed in the Future Research section in Chapter 6. The four activities were as follows:

- Install equipment.
- Verify equipment operation.
- Collect and compile data.
- Analyze data.

SITE SELECTION

The research team contacted other districts but found that two intersections in the Austin District and two intersections in the Houston District would serve the needs of this project best. Both districts were willing to support the research in terms of equipment and personnel needed to install and/or swap equipment.

TEST SITES

Through a process of phone calls to TxDOT districts and equipment vendors, TTI developed a list of candidate sites that met the needs of this project. Table 15 summarizes some pertinent information about each of the four sites.

Table 15. Summary of Selected Intersections.

District	Intersection	Test Direction	Prevailing Speed
Austin	FM 973/FM 969	Northbound/Southbound	60 mph
	FM 1431/Mayfield Ranch Blvd.	Eastbound	65 mph
Houston	FM 2920/Hannover Woods Dr.	Westbound	55 mph
	FM 1488/Kuykendall Blvd.	Eastbound	50 mph

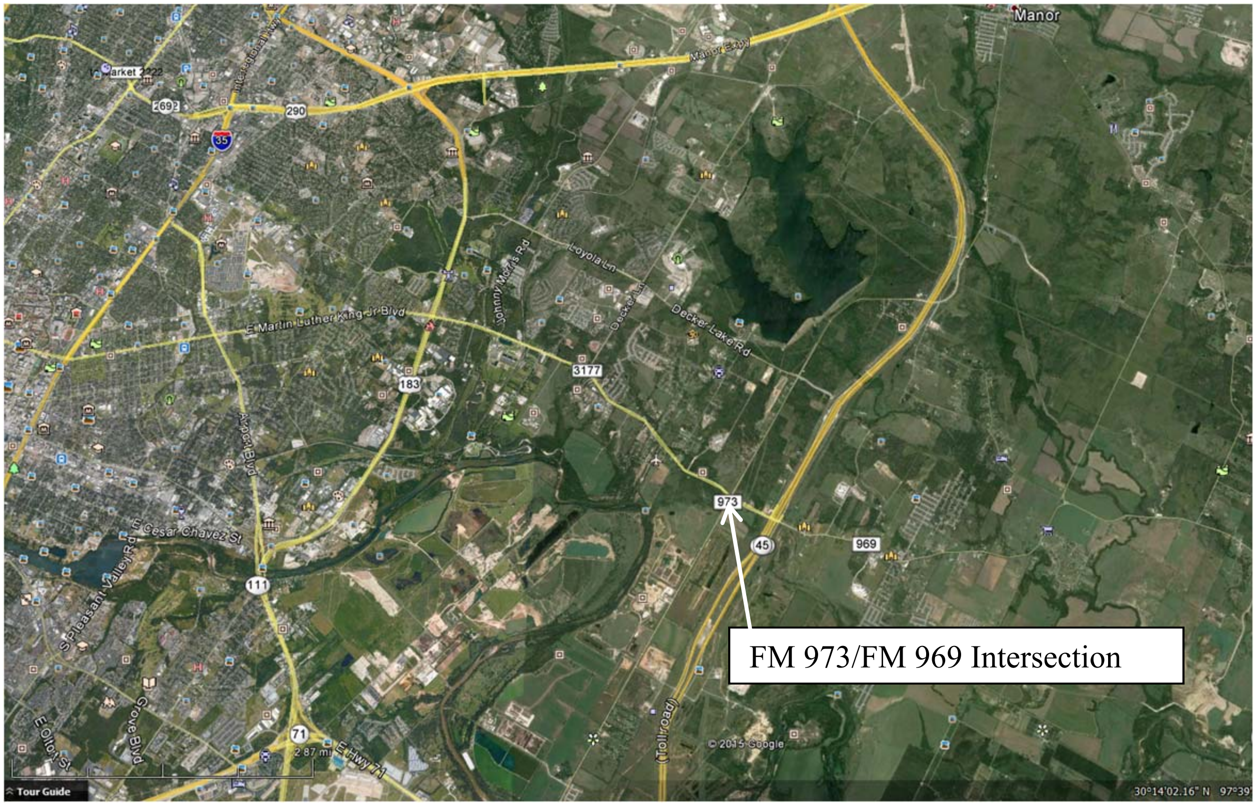
Austin District: FM 973/FM 969

Install Equipment

Table 16 lists the detector phasing and controller equipment for the FM 973 site. TxDOT had installed Trafficware Pods at this intersection within the previous two years according to district personnel, so its operational performance was expected to be similar to a new intersection. Figure 30 shows the location with respect to major roadways in the area. State Highway 130, a toll road, was just to the east of this intersection running parallel to FM 973. The intersection served significant truck traffic to the south, especially gravel trucks.

Table 16. FM 973/FM 969 Site Summary.

Detector(s) Tested	Approach/Phase/Channel	Controller	Ground Truth
Trafficware Pods at Stop Line	Northbound/Phase 3	Econolite ASC/3	Recorded Video
Trafficware Pods at Stop Line	Southbound/Phase 4		
Trafficware Pods Upstream	Northbound/Phase 11		
Trafficware Pods Upstream	Southbound/Phase 12		



FM 973/FM 969 Intersection

Source: Google Earth.

Figure 30. FM 973/FM 969 Site Location Map.

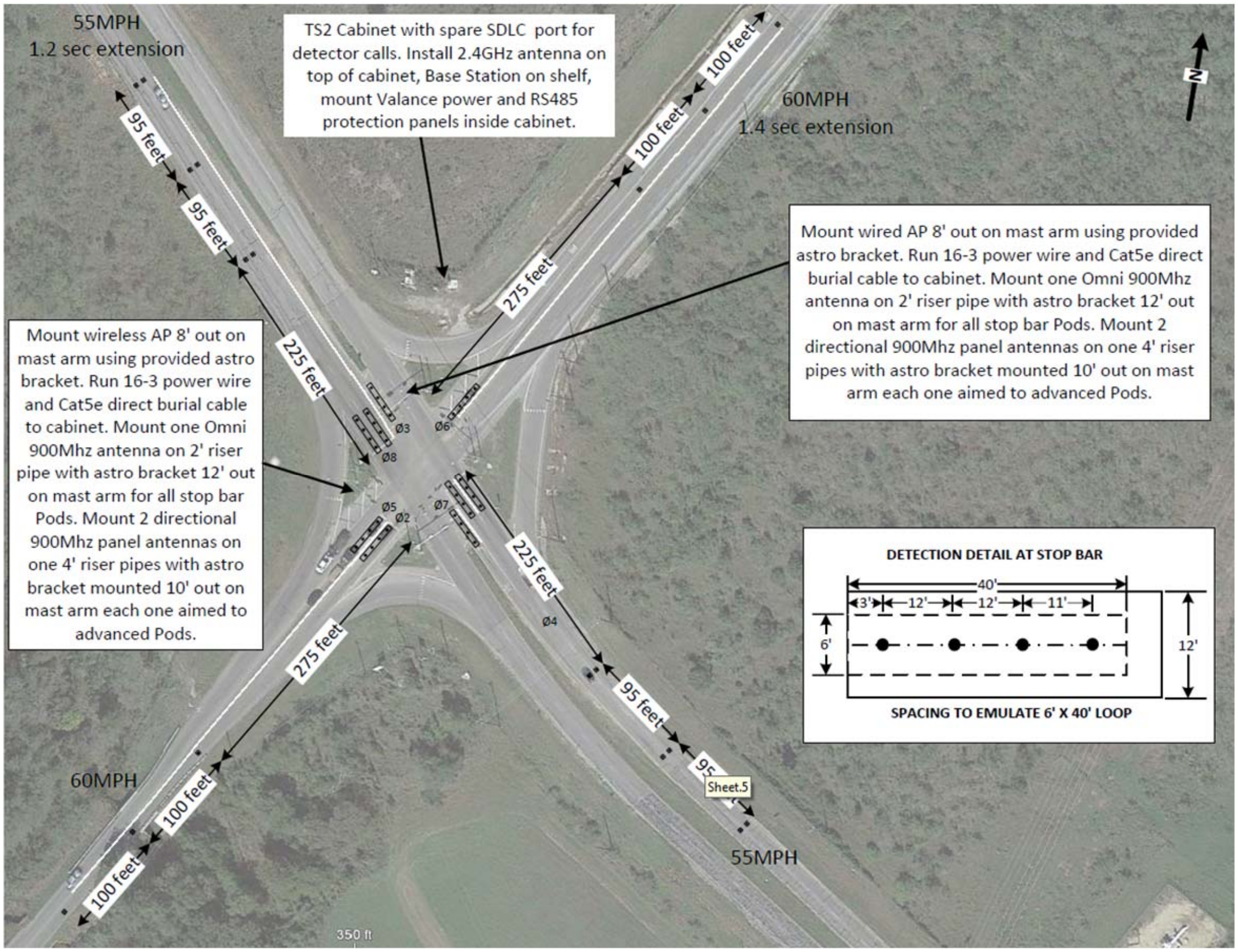
Verify Equipment Operation

Due to extensive data collection using the Pods at the TAMU Riverside campus, plus the fact that they are point detectors with simple on or off detections, TTI's data collection plan was to simply test selected detectors as simple counts for various vehicle types. This plan required comparing detections sent to the controller from selected detectors to recorded video. TTI contacted Trafficware before beginning the data collection to inform them that this site was being included in this research, but Trafficware representatives did not visit the site during data collection and apparently did not check or modify the setup.

Collect and Compile Data

Figure 31 shows a closer overhead view of the intersection with positions of Pods shown on each approach. The speed limit on the north and south approaches (FM 973) was 60 mph and the speed limit on the other two approaches was 55 mph. The controller was an Econolite ASC/3.

TTI monitored channels 3, 4, 11, and 12. Table 17 indicates the detectors representing these channels. Although this system would not normally be affected by weather or light conditions, TTI collected data during both daylight and nighttime.



TS2 Cabinet with spare SDLC port for detector calls. Install 2.4GHz antenna on top of cabinet, Base Station on shelf, mount Valance power and RS485 protection panels inside cabinet.

Mount wired AP 8' out on mast arm using provided astro bracket. Run 16-3 power wire and Cat5e direct burial cable to cabinet. Mount one Omni 900Mhz antenna on 2' riser pipe with astro bracket 12' out on mast arm for all stop bar Pods. Mount 2 directional 900Mhz panel antennas on one 4' riser pipes with astro bracket mounted 10' out on mast arm each one aimed to advanced Pods.

Mount wireless AP 8' out on mast arm using provided astro bracket. Run 16-3 power wire and Cat5e direct burial cable to cabinet. Mount one Omni 900Mhz antenna on 2' riser pipe with astro bracket 12' out on mast arm for all stop bar Pods. Mount 2 directional 900Mhz panel antennas on one 4' riser pipes with astro bracket mounted 10' out on mast arm each one aimed to advanced Pods.

Source: Trafficware.

Figure 31. FM 973/FM 969 Intersection Detector Plan from Trafficware.

Table 17. Channel Assignments and Test Intervals at FM 973/FM 969.

Channel	Detector/Approach	Time Interval
3	Northbound FM 973	11:43 a.m. to 1:30 p.m.
4	Southbound FM 973	
11	Northbound upstream	1:36 p.m. to 3:25 p.m.
12	Southbound upstream	

Austin District: RM 1431/Mayfield Ranch

Install Equipment

Figure 32 shows the location on RM 1431 with respect to major roadways in the area. The intersection is west of I-35 and east of FM 734 (Ronald Reagan Boulevard). Eastbound traffic on the test approach has sufficient distance from the nearest intersection to reach high speeds. Table 18 summarizes the signal phasing, controller type, and ground truth used at this intersection.

There is significant truck traffic along RM 1431, especially due to nearby gravel quarries. Terrain is hilly with a gradual upgrade for traffic approaching on the test approach from the west. This and adjacent signals along RM 1431 were operated in coordination mode during the following hours:

- Weekdays: 6:00 a.m. to 8:00 p.m.
- Weekends: 9:00 a.m. to 6:00 p.m.

Table 18. RM 1431/Mayfield Ranch Site Summary.

Detector(s) Tested	Approach/Phase	Controller	Ground Truth
Iteris Vantage Vector	Eastbound/Phase 2	Econolite ASC/3	Recorded Video
Wavetronix SS Advance (SS-200E)	Eastbound/Phase 2		
Wavetronix SS Matrix	Eastbound/Phase 5		

Detectors installed at this intersection prior to TTI collecting data were the Wavetronix SmartSensor Advance and Wavetronix SmartSensor Matrix. The Advance was not the Extended Range so the original detector for the eastbound approach was replaced with the SS-200E taken from the TAMU Riverside test site. Figure 33 shows the lane configuration of this intersection and other pertinent features.

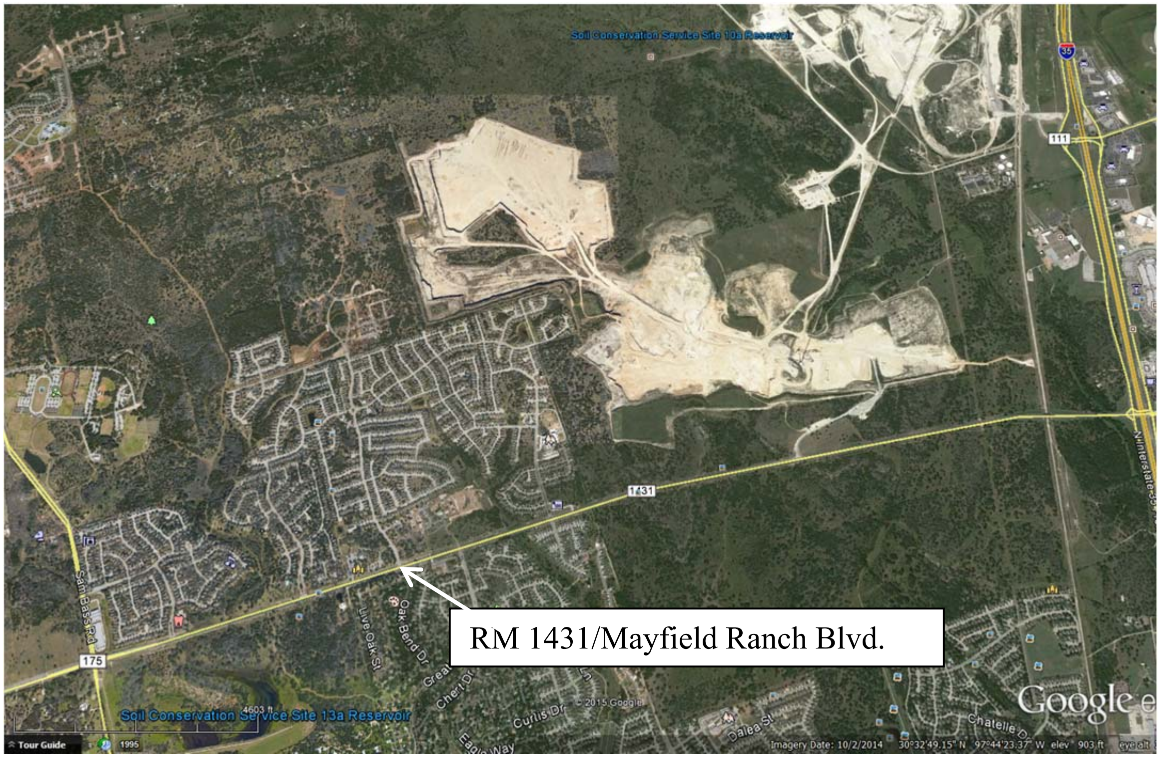
Verify Equipment Operation

A representative from Twincrest Technologies was on-site soon after installation to ensure that the detectors were working properly. The TxDOT crew also installed an Iteris Vantage Vector to be tested as part of this research. Two Iteris representatives were on-site during the installation and setup to verify the setup. TxDOT fastened the Iteris detector directly to the mast arm (not on a riser) facing west. The intersection had cameras installed but not being used, but the west-facing camera was inoperable at the time. For that reason, TTI used the video stream from the Iteris Vantage Vector as input to a DVR installed in the cabinet for ground truth but not while testing the Iteris detector.

Collect and Compile Data

Several changes were necessary at this intersection during the course of data collection. When the researchers first visited this intersection, TxDOT was using a Wavetronix Advance to control Phase 2 (eastbound through) and a Wavetronix Matrix for Phase 5 (eastbound left turns). TTI requested that TxDOT replace the existing Advance with the Advance SmartSensor 200E and install the Iteris Vantage Vector facing the same direction. TxDOT swapped the Advance and installed the Iteris Vantage Vector on the same day.

TTI initially requested that the Iteris be available for testing first, so TxDOT and Iteris representatives set their detector to control phases 2 and 5. One reason for postponing data collection with the Wavetronix Advance was that the Twincrest Technologies representative was not available to check its settings until the following week. An issue that Iteris reps were apparently not initially aware of was that each tripline had to be mapped to its own individual channel in the controller instead of to the same channel as it was initially set up. TTI discovered the problem while evaluating the data and alerted Iteris immediately. When Iteris corrected the issue, they found that there were not enough channels available to operate both phases 2 and 5, so they reconnected the Wavetronix Matrix to control phase 5 while the Iteris only controlled phase 2 (thru phase). TTI collected new Iteris data to replace the problematic data. Table 19 summarizes the major activities and dates in a concise format. Besides these activities, TTI connected periodically with the on-site laptop using TeamViewer software. TTI collected data during both daylight and nighttime. No rain or fog conditions occurred during this period.



RM 1431/Mayfield Ranch Blvd.

Source: Google Earth.

Figure 32. RM 1431/Mayfield Ranch Blvd. Site Location Map.

Source: Google Earth.

Figure 33. Lane Configuration for RM 1431/Mayfield Ranch Blvd.

Table 19. Major Activities at RM 1431/Mayfield Ranch Blvd.

Date	Activity	Comment
July 24	TTI & TxDOT installed Iteris Vector and Wavetronix Advance (SS-200E)	Iteris begins controlling EB approach phases 2/5
July 24–28	Collect initial data with Iteris	Not set up properly
July 28	Twincrest met TxDOT at site to check detectors and left them controlling the EB approach	Turned off Iteris
July 28–31	Collected data with Wavetronix Advance (phase 2) and Matrix (Phase 5)	Iteris still off
July 31	TxDOT and Iteris reps on-site to reprogram the controller and restart data collection with Iteris but keep Matrix monitoring phase 5	Set the three upstream Iteris detectors to individual channels.
July 31–Aug 5	Collected data with Iteris.	This is first Iteris data at this site that is based on proper setup
August 5	TTI returned to Austin to switch back to the Wavetronix Advance (phase 2) and keep Matrix monitoring left turns (phase 5)	Started DVR recording for Wavetronix Advance and connected to Iteris video for ground truth
August 5–7	Collected data with Wavetronix	DVR1 memory full on Aug. 7
August 7	TTI returned to Austin to replace SD memory card in DVR and checked clock drift between DVR, Laptop, and controller	Replaced with larger DVR2 SD card (64 Gigabyte)
August 7–10	Collected data with Wavetronix and recorded video on DVR	Final data collection at this site

A major objective at this site was to test the truck detection performance of the Wavetronix Advance SS-200E. During the setup of the Advance, a Twincrest Technologies representative set the truck detection distance at 850 ft but researchers discovered before leaving the site that it seemed to detect not only trucks but also some non-trucks at that distance. Twincrest recommended increasing the distance to a larger value so researchers increased it to 860 ft. The two components of this test of the Advance were: a) determine its accuracy in detecting trucks vs. non-trucks, and b) determine how much controller extension time it provided for vehicles it classified as trucks (and non-trucks). Twincrest set 2.5 to 7.5 sec for trucks and 2.5 to 5.5 sec for non-trucks.

Houston District: FM 2920/Hannover Woods

Install Equipment

Table 20 summarizes the site equipment and detectors tested. Ground truth in this case was recorded video captured by the Aldis GridSmart cameras for both day and night conditions. One of the salient features of the Aldis system is its ability to very easily store video data by simply plugging in an external hard drive into its USB port. The analysis used both the fisheye camera mounted within the intersection and the rectilinear camera facing west. The fisheye camera had previously been installed, but TxDOT added a camera for upstream detection with the support of Texas Highway Products. TxDOT was not using the fisheye camera for intersection control prior to this data collection effort, but the field crew switched it over before testing began. The upstream camera was only used for the tests and not for intersection control. This and adjacent signals along FM 2920 were operated in coordination mode from 6:00 a.m. to 8:00 p.m. Cycle lengths: were as follows

- 6 to 9 a.m. – 120 sec.
- 9 to 11 a.m. – 90 sec.
- 11 a.m. to 3:30 p.m. – 120 sec.
- 3:30 to 8 p.m. – 150 sec.

Table 20. FM 2920/Hannover Woods Site Summary.

Detector(s) Tested	Approach/Phase	Controller	Ground Truth
Aldis GridSmart Fisheye Camera	Eastbound/Phase 6	Econolite ASC/3	Recorded Video
	Westbound/Phase 2		
	Westbound Phase 5		
	Westbound Phase 1		

Figure 34 shows an area map of the intersection in relation to the surrounding road network in the north Houston/Spring area, and Figure 35 shows the lane configuration of this intersection and other pertinent features. FM 2920 is a major east-west arterial street with two through lanes in each direction and a single left-turn lane on each major street approach. The speed limit approaching from the west is 55 mph and from the east it is 50 mph. The north leg of the intersection leads to a residential area bordered by commercial development along the street, and the south leg is a short connector to a commercial area.

Source: Google Earth.

Figure 34. FM 2920/Hannover Woods Drive Site Location Map.

Source: Google Earth.

Figure 35. Lane Configuration for FM 2920/Hannover Woods Drive.

Verify Equipment Operation

A representative from Texas Highway Products was on-site to install the rectilinear camera facing eastbound upstream traffic. He checked the fisheye camera mounted on the northwest corner of the intersection as well as the Aldis processor that was already installed at the site. Only the fisheye camera was being used to control the intersection, while the upstream camera was only being used for research purposes. The detector controlling the upstream portion of the approach was a Wavetronix Advance. Twincrest Technologies checked the Advance to determine how well it was operating and recommended using the FM 1488 intersection instead of this one since the Advance installed there was operating better.

Collect and Compile Data

TTI placed a laptop PC in the cabinet to monitor the controller operation and connected an external hard drive to the Aldis GridSmart processor to store video. Once started, TTI left the equipment in place for five days to collect non-stop data on a 24-hour a day basis. TTI collected data during both daylight and nighttime. No rain or fog conditions occurred during this period.

Houston District: FM 1488/Kuykendall Boulevard

Install Equipment

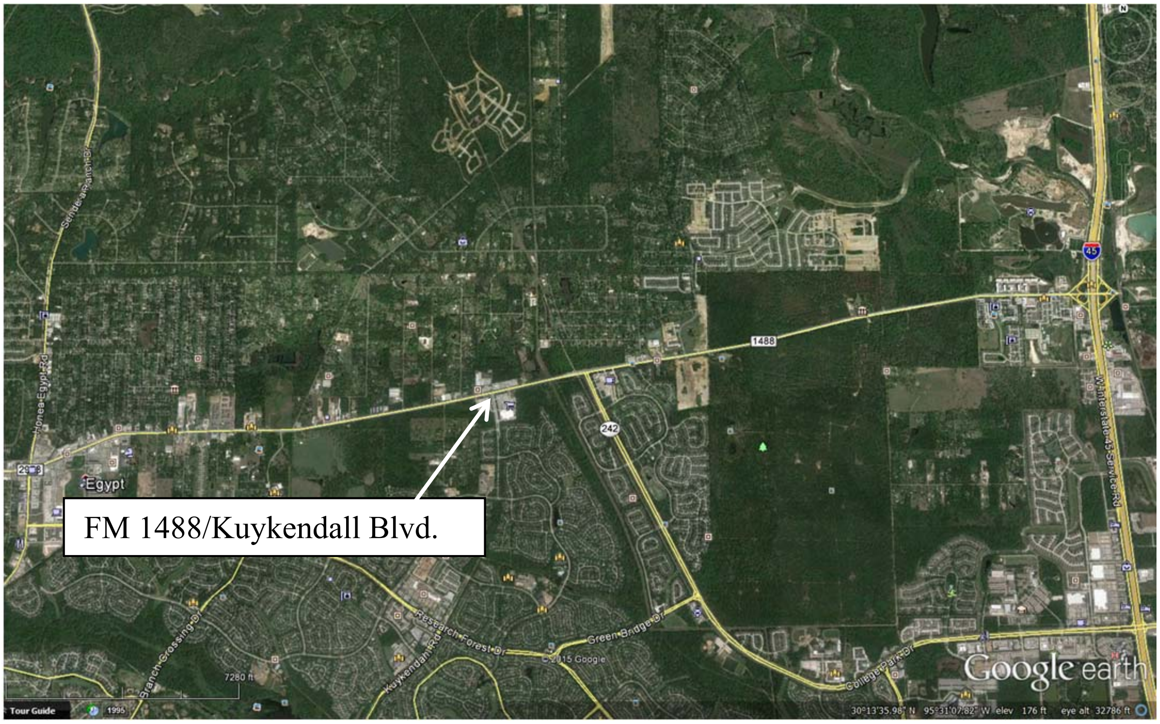
Table 21 summarizes the equipment that was either already installed at this intersection or was installed for research purposes. Upon request by the research team, TxDOT installed the infrared camera facing west. Power and communications cables had been used previously for video detection but were not in use during this test, so TTI and a FLIR/Traficon representative were able to utilize them with the infrared camera and the VIP card in the cabinet. This and adjacent signals along FM 1488 were operated in coordination mode during the following hours:

- Weekdays: 5:45 a.m. to midnight.
- Weekends: 8:00 a.m. to midnight.

Table 21. FM 1488/Kuykendall Blvd. Site Summary.

Detector(s) Tested	Approach/Phase	Controller	Ground Truth
FLIR VIP with IR Camera	Eastbound/Phase 2	Econolite ASC/3	Recorded Video
Wavetronix SS Advance	Eastbound/Phase 2		
Wavetronix SS Matrix	Eastbound/Phase 5		

Figure 36 shows an area map of the intersection in relation to the surrounding road network, and Figure 37 shows the lane configuration of this intersection and other pertinent features. Prevailing speeds on both approaches to this intersection are 55 mph or higher. The cross-section provides for two through lanes on each main street approach and a single left-turn lane. Both sides of FM 1488 are built up with commercial strip development, and the south approach leads to a relatively large single family residential area. The topography in the area is flat with a slight rise in elevation looking west from the intersection. The westbound approach had better sight distance, but several factors precluded using that approach.



Source: Google Earth.

Figure 36. FM 1488/Kuykendall Blvd. Site Location Map.

Source: Google Earth.

Figure 37. Lane Configuration for FM 1488/Kuykendall Drive.

Verify Equipment Operation

The FLIR/Traficon representative from Control Technologies was on-site to ensure optimal operation of the video detection system once installed. Also, a representative of Twincrest Technologies was on-site during the installation to check the Wavetronix Advance and the Wavetronix Matrix installed there. TxDOT provided a bucket truck and personnel to tweak the orientation of test detectors as directed by each product representative. Even though the initial attempt at installation on July 29 was only partially successful, TTI returned and met TxDOT and Control Technologies at the intersection again on July 31 to finish the installation. TTI personnel placed a laptop PC in the cabinet to monitor the controller and recorded video from the infrared camera onto a DVR placed in the cabinet.

Collect and Compile Data

Data collection occurred over a period of two days, again beginning on July 31. Ground truth for the effort came from the infrared camera and recorded video. Light conditions for this effort involved only day and night. No rain or fog conditions occurred during this period.

CHAPTER 5. DATA COLLECTION RESULTS

INTRODUCTION

This chapter provides results from the extensive literature search, the Riverside tests, and the four intersection tests. In a few cases weather conditions could be included in field data collection, but most of the conditions were dry daytime or dry nighttime conditions. The literature results can provide supplemental weather data. This chapter begins by covering the analysis metrics used in this research. One broad category is simply presence detection, which is typically used at the stop line, incorporating the following possible outcomes:

- Correct detection.
- Missed calls.
- False calls.
- Dropped calls.
- Stuck-on calls.

For convenience, the description of these metrics covered in Chapter 3 is reproduced below:

- Missed calls, including:
    - Vehicles passing between two monitored lanes.
    - Vehicles passing directly through the detection zone.
- False calls, including:
    - Calls received when no vehicle is present.
    - Calls received when a vehicle is present in the adjacent lane but not the observed lane.
    - Multiple calls received due to flickering when only one vehicle is present.
- Dropped calls (i.e., calls that end while the vehicle is still present in the detection zone).
- Stuck-on calls (i.e., calls that do not end when the vehicle leaves the detection zone).

LITERATURE RESULTS

Early comparisons by Middleton et al. (*34*) of the Wavetronix SmartSensor Advance against a system with three inductive loops per lane indicated only modest changes in red-light running but significantly improved ability to find gaps in the traffic stream to terminate the main street green phase. A limiting factor with this research was a passage time of 200 milliseconds in the controller for the main street phases being too short and/or the dilemma zone travel time range of 2.5 to 5.5 sec. At that time, both the vendor and the equipment were relatively new, so the setup was likely suboptimal. Due to the large number of large trucks using this intersection, the dilemma zone travel time range should have been expanded to perhaps 2.0 to 6.0 sec and the passage time increased to 1.0 sec.

Sharma et al. (*42*) later tested a similar SmartSensor Advance, finding that, although the detector should have demonstrated superior dilemma zone protection when compared to point detectors, the results were mixed. For the four identified metrics, the authors offered the following summary:

- Accurately detect vehicle entry: Performance of the detector was substandard due to excessive number of false detections generated by turning traffic and standing queues. It counted three to four undetected vehicles per hour.
- Accurately track vehicle position: Detector performance was good. The only problem was a fixed bias in one direction which could be removed by fine-tuning the sensor in the field.
- Accurately track vehicle speed: Detector performance was satisfactory. In a few cases, it did not update speeds beyond a point in time, particularly when adjacent vehicles were moving closely together.
- Accurately detect vehicle exit: Performance was seriously affected by turning traffic and standing queues.

In summary, the detector showed potential for improving both the safety and efficiency of dilemma zone protection compared to point detectors. However, it needs improvement in its detection and tracking accuracy, particularly when used on approaches with significant turning traffic

Performance of the Wavetronix SmartSensor Matrix in detecting vehicles varied significantly depending on where it was placed. Its accuracy varied from a low of about 72 percent at the stop line to as high as 99+ percent at a mid-block location (*33*). Medina et al. (*35, 36, 37*) evaluated the Matrix's performance in adverse weather conditions. Performance was excellent except for false calls during snow (48 percent errors).

Medina et al. (*35, 36, 37*) tested wireless magnetometers and two radar detectors, finding that false calls were high, especially for the Wavetronix SmartSensor Advance during periods of snow (48 percent at stop line and 30 percent upstream). The Sensys was also higher than expected at the stop line for normal, snow, and rain events (15, 17, and 12 percent, respectively).

Medina et al. (*35, 36, 37*) also tested three video image detection systems using the same methodologies as used for other technologies and in inclement weather conditions. Missed calls at the stop line are almost nonexistent throughout all weather conditions (light fog, dense fog, daytime rain, daytime snow, and nighttime rain). Missed calls for advance zones are reasonably low for light fog (less than 3 percent), daytime rain (less than 3 percent), and nighttime rain (less than 12 percent), but they are unacceptably high in other inclement weather conditions. False calls are usually high under all inclement weather conditions.

Chitturi et al. (*41*) found problems with video detection due to different light conditions such as shadows from adjacent lane vehicles and due to crossing or turning vehicles, pedestrians, and even exhaust fume clouds. Where no adjacent lane shadows are cast, the false-call rate was very low (never more than 4 percent). False calls were as high as 45 percent during periods of longer shadows in zone 1 (innermost lane of the approach). The use of infrared cameras can solve some problems in video imaging but not all. Iwasaki et al. (*32*) found that, even with IR cameras, false calls and missed calls went from 1.3 percent and 3.7 percent, respectively, in good environmental conditions to 3.4 percent and 7.2 percent, respectively, when ambient temperatures nearly equal vehicle components targeted for detection.

Hurwitz et al. (*44*) tested the Wavetronix SmartSensor Advance and found that drivers experienced less difficulty deciding to stop or proceed under radar sensor control compared to point detection. The authors also determined that radar reduced the rate of red-light-running but the difference was not statistically significant.

RIVERSIDE RESULTS

The following results for Riverside tests begin with tabular results followed by Box and Whisker plots. Box plots are part of the descriptive statistics used to display the data in an intuitive way for quick and easy understanding. Results from the use of GPS are included at the end of this section.

Detector Tabular Results

To understand the results that follow regarding detector accuracy, one must understand the tolerances applied to each detector for each of the error categories. The tolerances were derived from a knowledge of each detector and applying the detector's accuracy characteristics from a reasonably large dataset. In general, once sufficient data were available, the analysis used those data and developed tolerance values that allowed modest errors to be counted as meeting the accuracy expectations. Table 22 summarizes the tolerances for each detector and speed of 50 mph or 70 mph. These tolerances apply to false calls, stuck-on calls, and dropped calls. For missed calls, the process was binary with only two results so a tolerance was not applied. The calculation for correct calls first removed missed, false, stuck-on, and dropped calls and the balance was calculated as correct. In other words, the correct call percentage was correct detections divided by the total number of events for that sample as measured by timestamps at the controller. For vehicle type, "car" is a sedan, minivan, SUV, or pickup; and "truck" is a large Class 8 truck-tractor.

The tolerances summarized in Table 22 yield the summary results shown in Table 23 for each detector by speed (50 mph or 70 mph) and weather/light condition (day, dry; day, rain; transition, dry; and night, dry). The methodology used for these results comes from the section titled Detector Verification on page 57. Shaded cells indicate that no data are available for that condition. For example, the Iteris tripline at 566 ft should never be activated at 50 mph as indicated by the blank cells for that condition. In other cases, cells are blank because insufficient data exist for comparison purposes. In some cases, the research team collected data but it was determined to be flawed upon further analysis. In other cases, the condition (e.g., rain) did not occur at an opportune data collection event. Stop line results treat dropped calls and stuck-on calls as correct calls in this table but their values are included in Appendix C, which has the complete results based on both the correct detection values and the error values for each category shown in Table 23. It also includes the sample sizes for each category.

The research team also collected motorcycle data with all detectors except the Trafficware Pods. The reason the Pods were excluded was due to having to mount them on the pavement surface and not flush with the surface. Other vehicles could simply straddle the Pods but the motorcycle could only pass near each Pod. The results were inconclusive for Pod detection because the motorcycle did not always pass at the desired distance from each Pod. Without the Pod data to determine the motorcycle location, this result is simply presence detection accuracy. Table 24 provides the results for the other detectors.

Table 22. Detector Tolerances Used to Determine Accuracies.

Speed (mph)	Detector	Definitions of Calls by Call Type		
		False	Stuck-On	Dropped
50 or 70	FLIR VIP	-5 ≤ TT ≤ 20	F, PT > 0.75 s	F, PT < 0.25 s
50 or 70	Iteris Stop Line	-5 ≤ TT ≤ 20	F, PT > 1 s	F, PT< 0.5 s
50 or 70	Iteris Tripline at 485 ft	-5 ≤ TT ≤ 20	F, PT > 3.8 s	F, PT < 3.2 s
50 or 70	Iteris Tripline at 566 ft	-5 ≤ TT ≤ 20	F, PT > 3.8 s	F, PT < 3.2 s
50 or 70	Wavetronix Matrix	-5 ≤ TT ≤ 20	F, PT > 2.5 s	F, PT < 1 s
50 or 70	Wavetronix Advance	-5 ≤ TT ≤ 20	F, PT > 3.5 s	F, PT < 2.5 s
50 or 70	Aldis Upstream	2 ≤ TT ≤ 20	F, PT > 6 s	F, PT < 2 s
50 or 70	Aldis Stop Line	-5 ≤ TT ≤ 2	F, PT > 2.5 s	F, PT < 1 s
50	Pod 100 ft from stop line	0.6 ≤ TT ≤ 1.8	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
50	Pod 200 ft from stop line	2 ≤ TT ≤ 3.2	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
50	Pod 300 ft from stop line	3.3 ≤ TT ≤ 4.5	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
50	Pod 400 ft from stop line	4.7 ≤ TT ≤ 5.9	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
50	Pod 500 ft from stop line	6.1 ≤ TT ≤ 7.3	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
50	Pod 600 ft from stop line	7.5 ≤ TT ≤ 8.7	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
50	Pod 700 ft from stop line	8.8 ≤ TT ≤ 10	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
50	Pod 800 ft from stop line	10.2 ≤ TT ≤ 11.4	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
50	Pod at stop line	-0.8 ≤ TT ≤ 0.4	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod 100 ft from stop line	0.3 ≤ TT ≤ 1.5	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod 200 ft from stop line	1.2 ≤ TT ≤ 2.4	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod 300 ft from stop line	2.3 ≤ TT ≤ 3.5	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod 400 ft from stop line	3.2 ≤ TT ≤ 4.4	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod 500 ft from stop line	4.2 ≤ TT ≤ 5.4	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod 600 ft from stop line	5.2 ≤ TT ≤ 6.4	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod 700 ft from stop line	6.1 ≤ TT ≤ 7.3	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod 800 ft from stop line	7.1 ≤ TT ≤ 8.3	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s
70	Pod at stop line	-0.7 ≤ TT ≤ 0.5	F, PT > 0.5 s (car), PT > 0.7 s (truck)	F, PT < 0.1 s

Notes:
TT= travel time to stop line during off record, seconds.
PT=presence time, seconds.
M= A run was conducted with the device active, but no call was received from the device during the run.
F= A call was received from the device during the test run and not determined to be false.
C= A call was received from the device during the test run, and the call was not determined to be false, stuck-on, or dropped.

Table 23. Correct Riverside Detection Rates Based upon Point Detection and Speed. [a]

	50 mph				70 mph			
Detector	**Day, Dry**	**Trans, Dry**	**Night, Dry**	**Day. Rain**	**Day, Dry**	**Trans, Dry**	**Night, Dry**	**Day, Rain**
FLIR VIP Stop Line [b]	94.01%	95.74%	98.14%	97.67%	97.39%	▨	99.44%	95.65%
Iteris Stop Line [b]	93.83%	100.00%	▨	71.43%	78.79%	100.00%	▨	0.00%
Iteris Trip at 485 ft	79.01%	93.33%	▨	95.24%	87.88%	72.73%	▨	56.41%
Iteris Trip at 566 ft	▨	▨	▨	▨	39.39%	72.73%	▨	48.72%
Wavetronix Matrix [b]	101.30%	▨	97.56%	106.90%	97.92%	▨	▨	90.00%
Wavetronix Advance	94.81%	▨	97.56%	96.55%	97.92%	▨	▨	96.67%
Aldis Upstream	75.46%	67.77%	98.90%	85.78%	6.55%	0.00%	100.00%	0.00%
Aldis Stop Line [b]	79.60%	87.60%	98.14%	100.43%	92.09%	100.00%	100.00%	100.00%
Pod 100 ft from stop	91.17%	99.17%	98.14%	92.67%	97.96%	100.00%	99.44%	100.00%
Pod 200 ft from stop	90.35%	97.52%	99.07%	95.26%	97.96%	100.00%	98.33%	100.00%
Pod 300 ft from stop	90.35%	98.35%	97.67%	93.97%	98.30%	100.00%	100.00%	98.55%
Pod 400 ft from stop	91.38%	97.52%	97.67%	92.24%	96.60%	100.00%	99.44%	98.55%
Pod 500 ft from stop	90.35%	97.52%	95.35%	94.40%	96.26%	96.97%	100.00%	97.10%
Pod 600 ft from stop	86.86%	95.87%	94.42%	87.50%	96.60%	100.00%	99.44%	100.00%
Pod 700 ft from stop	89.32%	96.69%	95.35%	90.52%	97.62%	100.00%	100.00%	97.10%
Pod 800 ft from stop	87.89%	95.04%	91.63%	88.36%	95.58%	100.00%	98.89%	100.00%
Pod at stop line	92.81%	96.69%	97.67%	91.81%	98.98%	100.00%	98.89%	98.55%

[a] Shaded cells indicate no data for that condition.

[b] Stop line results treat stuck-on and dropped calls as correct calls for stop line detectors.

Table 24. Riverside Summary Counts and Percents for Motorcycles.

			Count		Percent	
Detector	Channel	No. Runs	Miss	Not Miss	Miss	Not Miss
FLIR VIP Stop Line	SB5	53	2	51	3.77%	96.23%
Iteris Stop Line	SB13	28	0	28	0.00%	100.00%
Iteris Tripline at 485 ft	SB15	28	18	10	64.29%	35.71%
Wavetronix Matrix	SB17	25	0	25	0.00%	100.00%
Wavetronix Advance	SB21	25	0	25	0.00%	100.00%
Aldis Upstream	SB38	53	6	47	11.32%	88.68%
Aldis Stop Line	SB46	53	28	25	52.83%	47.17%
	Total	265	54	211	20.38%	79.62%

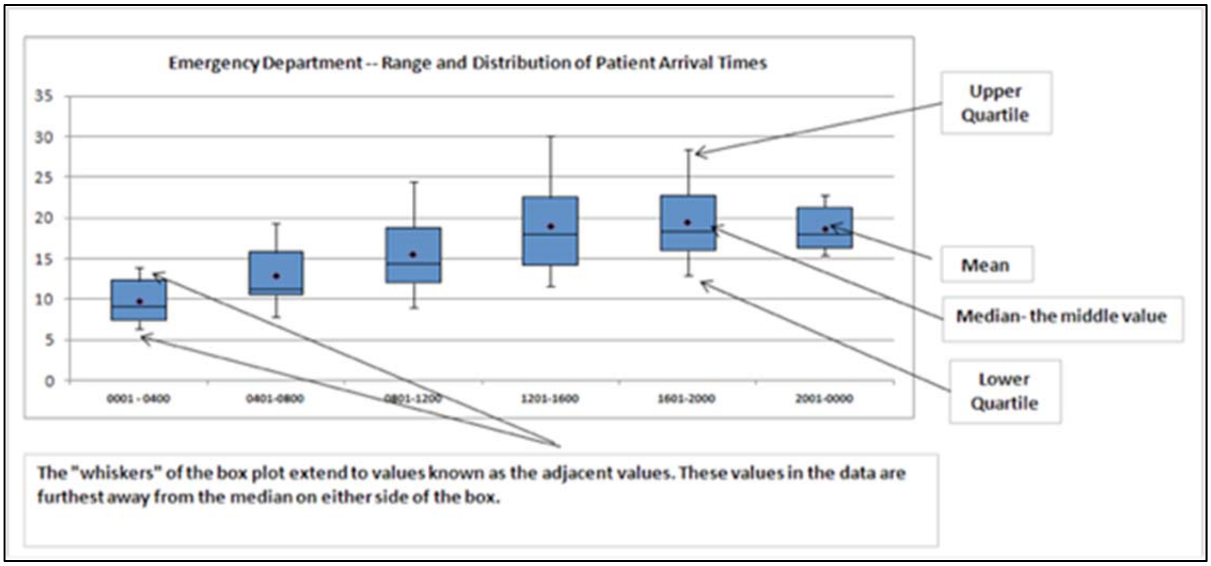
Detector Box and Whisker Plots

Figure 38 shows the common components of these plots for readers who might not be familiar with this tool. For detector results, the horizontal axis might indicate weather conditions or it might represent individual detector results. The vertical axis indicates the test results plotted according to the scale (e.g., in time or distance). The horizontal dimension of the box is not significant, only the vertical is significant.

Again, using Figure 38, the variables shown in the figure are described below:

- Mean (the dot inside the box): simple arithmetic mean (e.g., detector on time = sum of on-times for a given sample divided by n).
- Median (the band inside the box): the middle value (e.g., detector on time ranging from 3.0 sec to 4.0 sec with readings every 0.1s, median would be 3.5 sec).
- Lower and upper quartile: organize outcomes in order small to large, divide outcomes into four equal parts (quartiles), use lower and upper portions. The box consists of 1st and 3rd quartile.
- Whiskers: indicate values furthest away from the median (omitting outliers).
- Outliers (points outside the whiskers): sometimes plotted as individual points.

The following Riverside results are segregated by detector, first with stop line plots followed by upstream plots. Figure 39 through Figure 42 are stop line results and Figure 43 through Figure 51 are upstream results. The stop line plots are arranged alphabetically with Aldis first followed by Iteris (the Wavetronix Advance is only an upstream detector). Interpretation of the stop line presence time must consider that the stop line detector at TxDOT intersections is typically not used past the MIN GREEN setting in the controller but is still important from an intersection efficiency point of view. If, for example, the detector is sluggish in turning off, it might cause unnecessary delay to conflicting phases. Consistency when it turns on is also important from the standpoint of efficiency and predictability.



The "whiskers" of the box plot extend to values known as the adjacent values. These values in the data are furthest away from the median on either side of the box.

Figure 38. Example Box and Whisker Plot (*46*).

The upstream results indicate when the detector turned on and when it turned off in terms of travel time to stop line, followed by presence time calculated as the difference between the first two values. These on and off times are critical from the standpoint of protection of the indecision zone and are valued differently than the simple presence time needed at the stop line. In the case of the Wavetronix Advance and the Iteris Vantage Vector, the measurement of distance and speed has a direct correlation with how well each detector would protect motorists at the end of the green phase at high-speed intersections. In any case, consistency across all conditions is critical to being able to properly set up the controller. With its rectilinear camera, the Aldis GridSmart detector apparently only detects vehicles upstream but will eventually use that detection capability for green time extension.

Interpretation of these plots must consider that more desirable tighter grouping of the data is indicated by smaller boxes and shorter whiskers (as measured vertically). Also, boxes at the same position vertically within each plot indicate consistency across conditions (boxes at unchanging vertical positions), which indicates less variation. Chapter 6 contains the analysis of these results.

Appendix D contains a more complete summary of the data from which the box plots evolved. The data are segregated by speed, detector channel and light/weather conditions (day, transition, night, and rain). Table 25 through Table 30 summarize the critical metrics shown by the boxplots for most detectors such as mean on and off times, standard deviations, and total on times. Trafficware Pods are not included but are contained in Appendix D. These tables and graphics allow quick side-by-side comparisons of performance by environmental conditions (day, dry; transition, dry; night, dry; and day, rain).

Box and Whisker Plots for Stop Line Detection

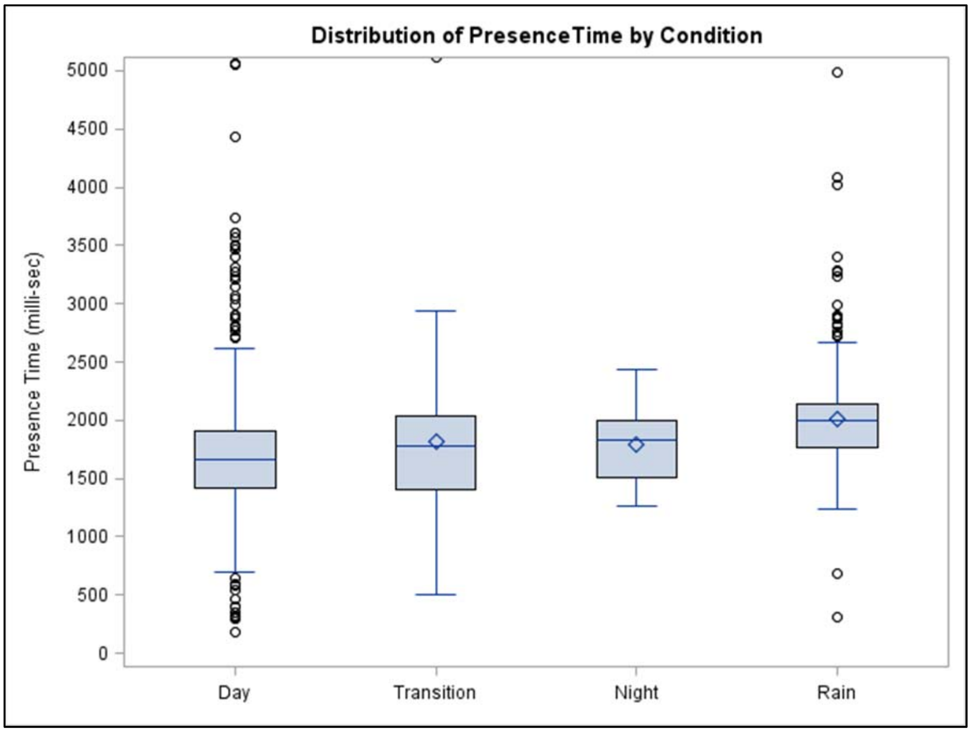


Figure 39. Box Plots of Presence Time by Aldis (SB 46) at the Stop Line.

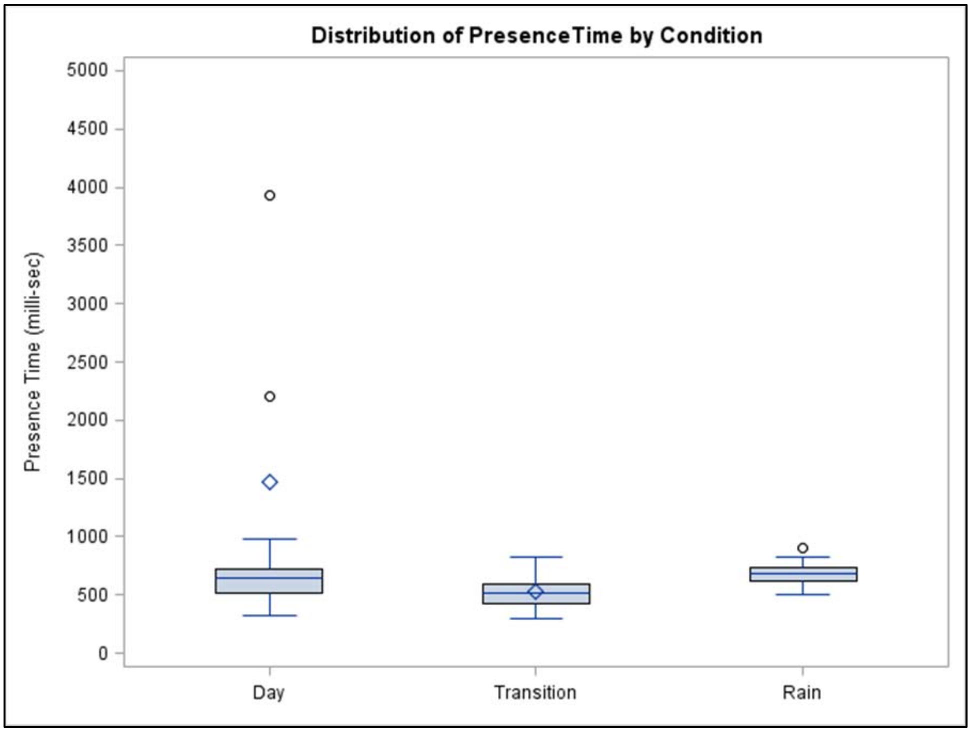


Figure 40. Box Plots of Presence Time by Iteris (SB 13) at the Stop Line.

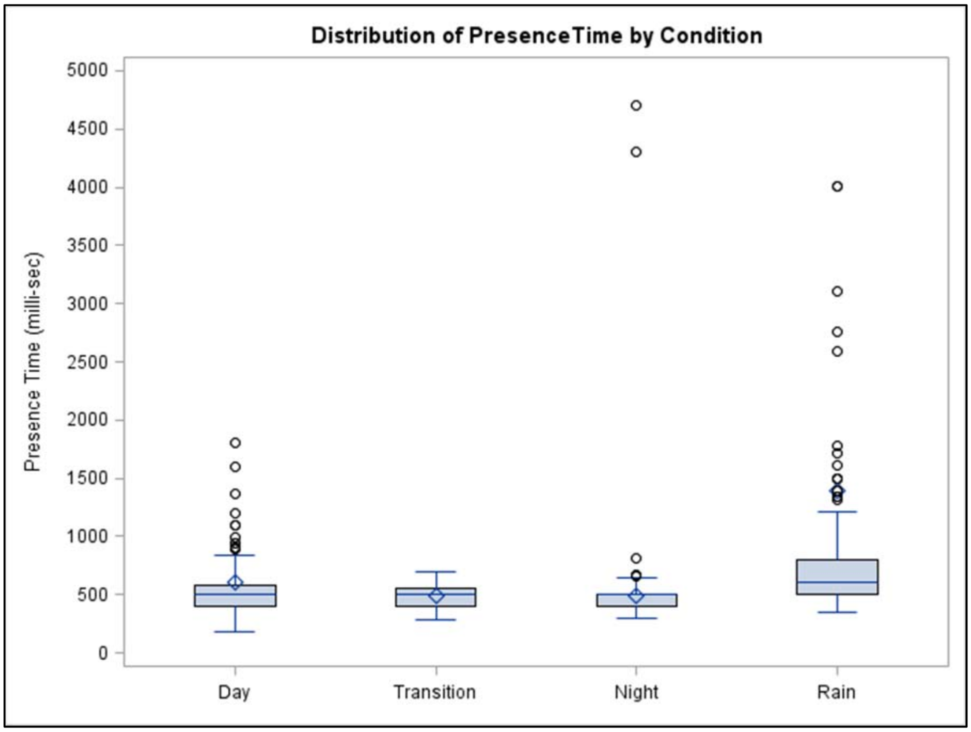


Figure 41. Box Plots of Presence Time by FLIR VIP (SB 5) at the Stop Line.

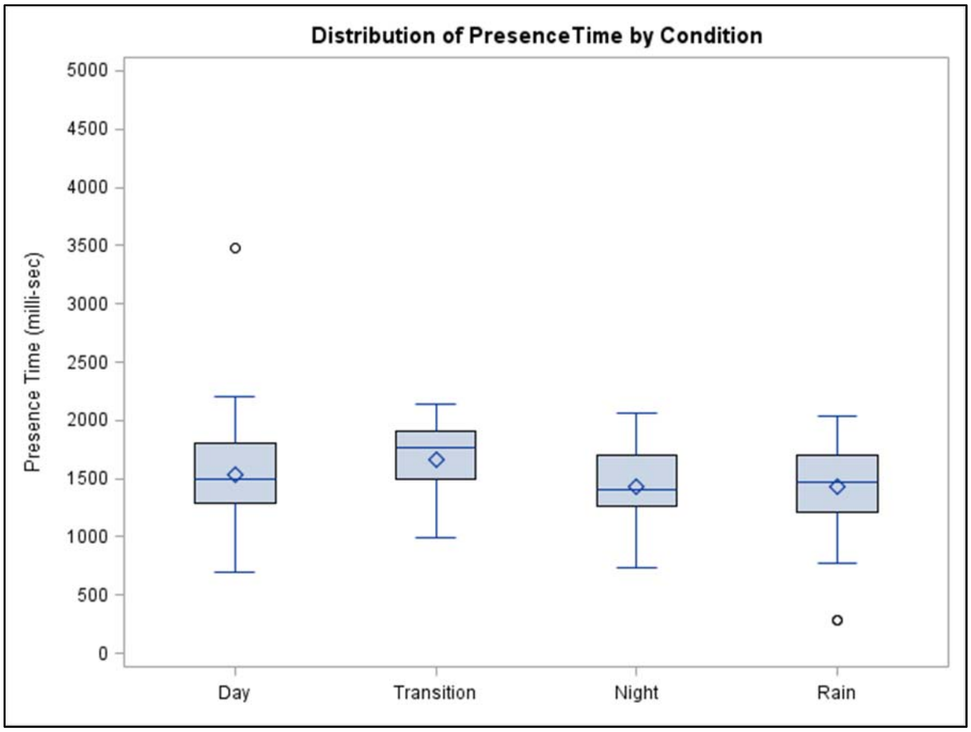


Figure 42. Box Plots of Presence Time by Wavetronix Matrix (SB 17) at the Stop Line.

Box and Whisker Plots for Upstream Detection

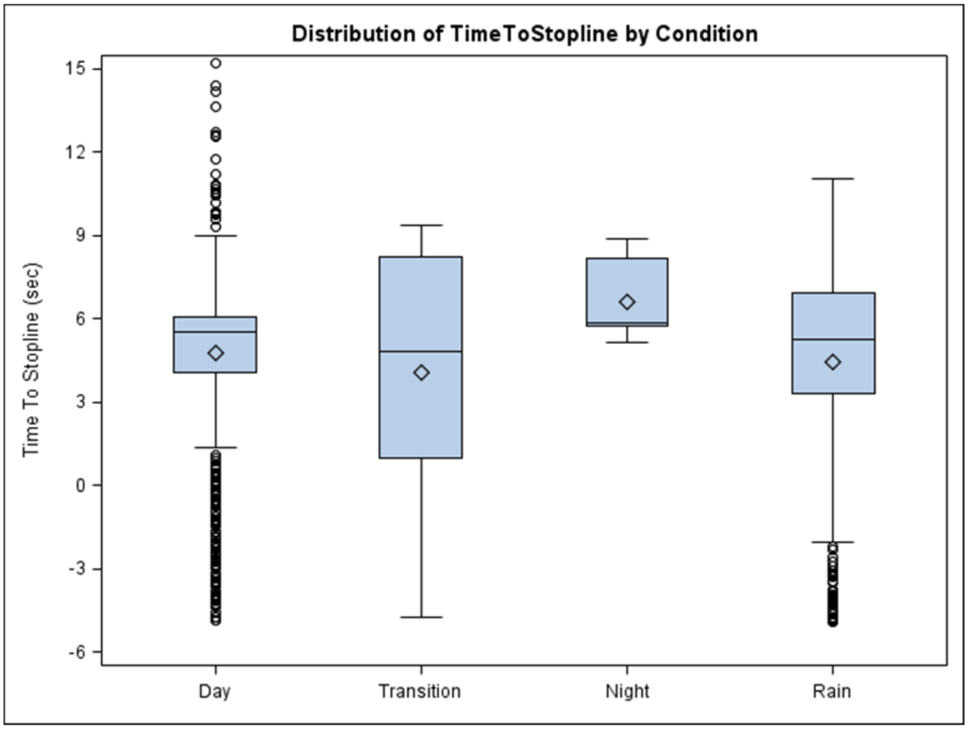


Figure 43. Box Plots of the Time to Stop Line when Aldis (SB 46) Turned On.

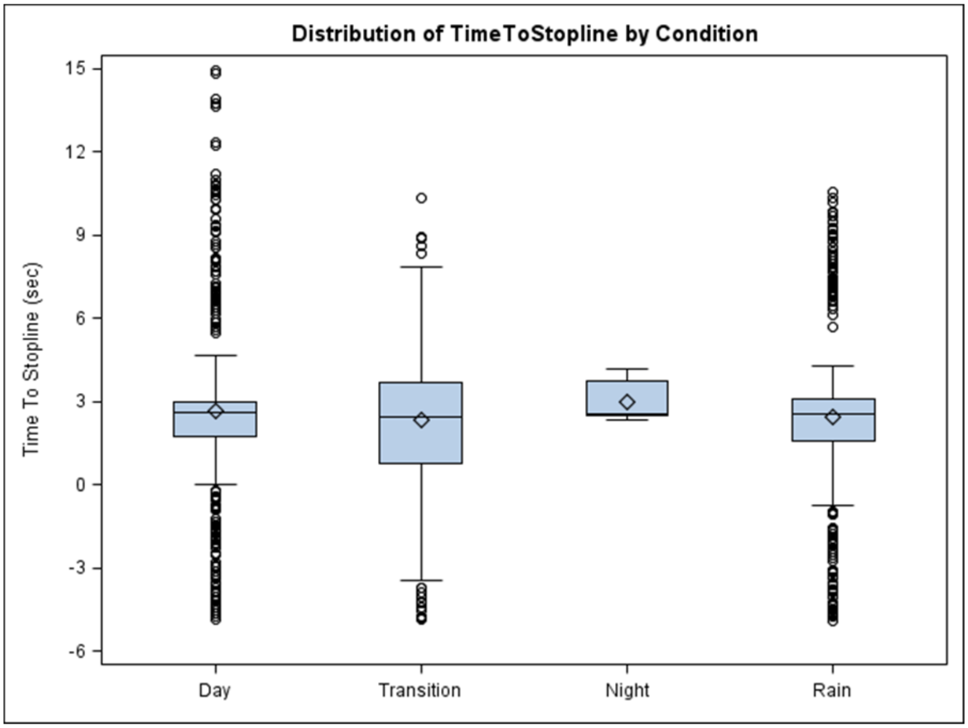


Figure 44. Box Plots of the Time to Stop Line when the Aldis (SB 46) Turned Off.

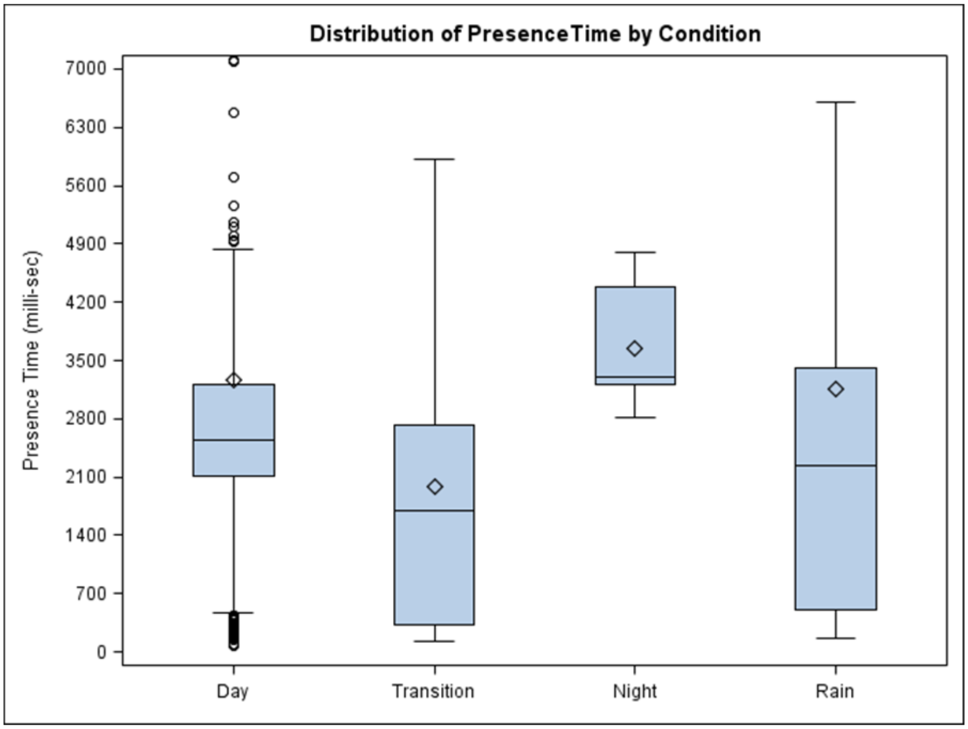


Figure 45. Box Plots of Presence Time by Aldis (SB 38) Upstream.

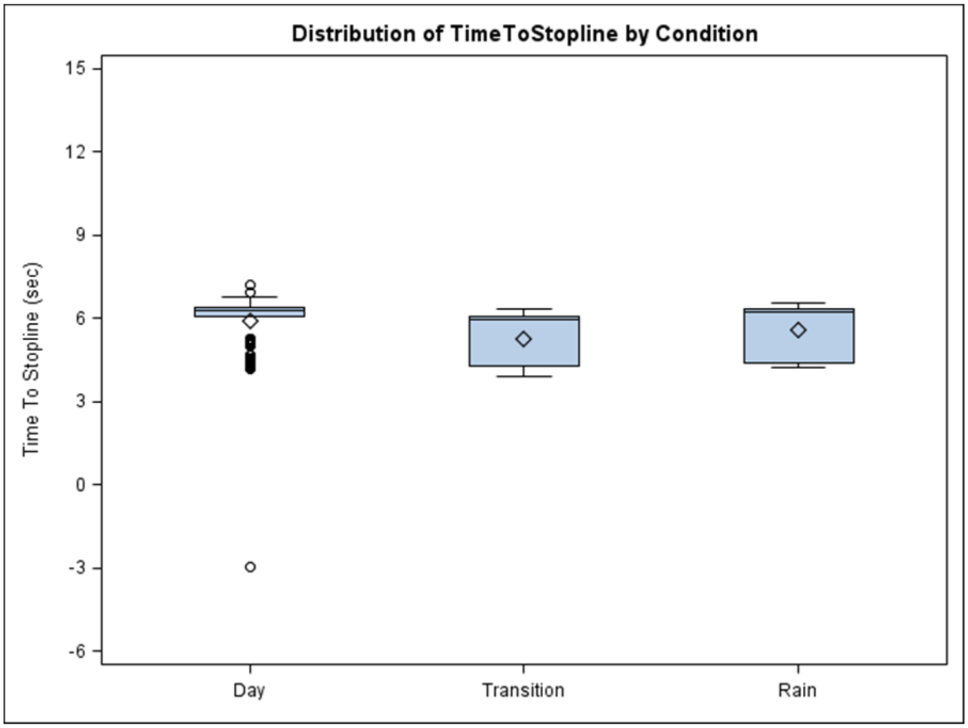


Figure 46. Box Plots of the Time to Stop Line when Iteris (SB 15) Turned On.

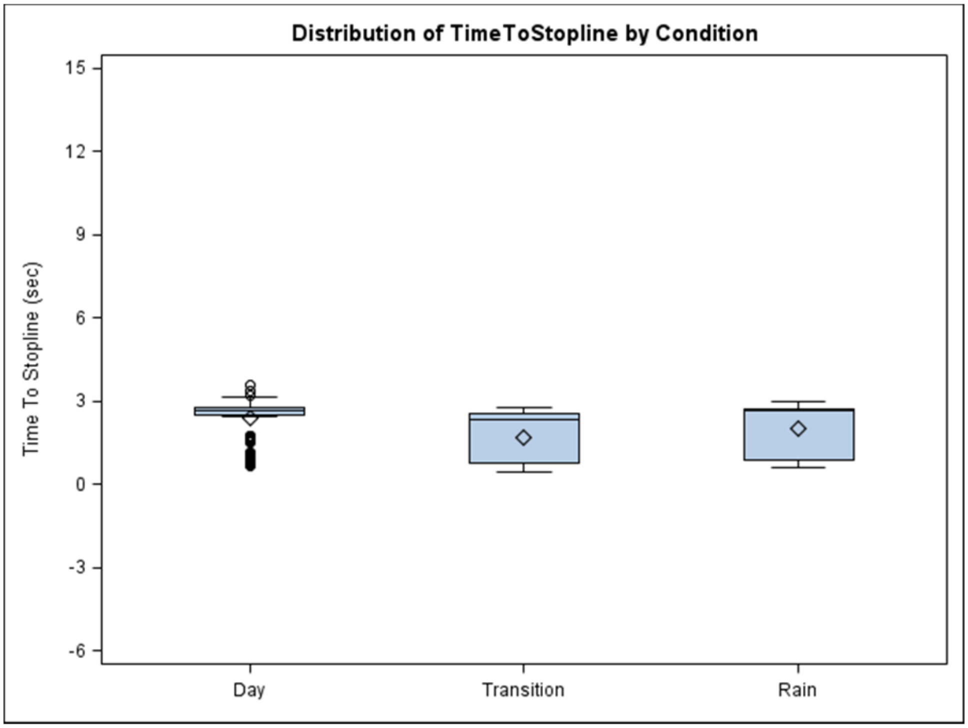


Figure 47. Box Plots of the Time to Stop Line when the Iteris (SB 15) Turned Off.

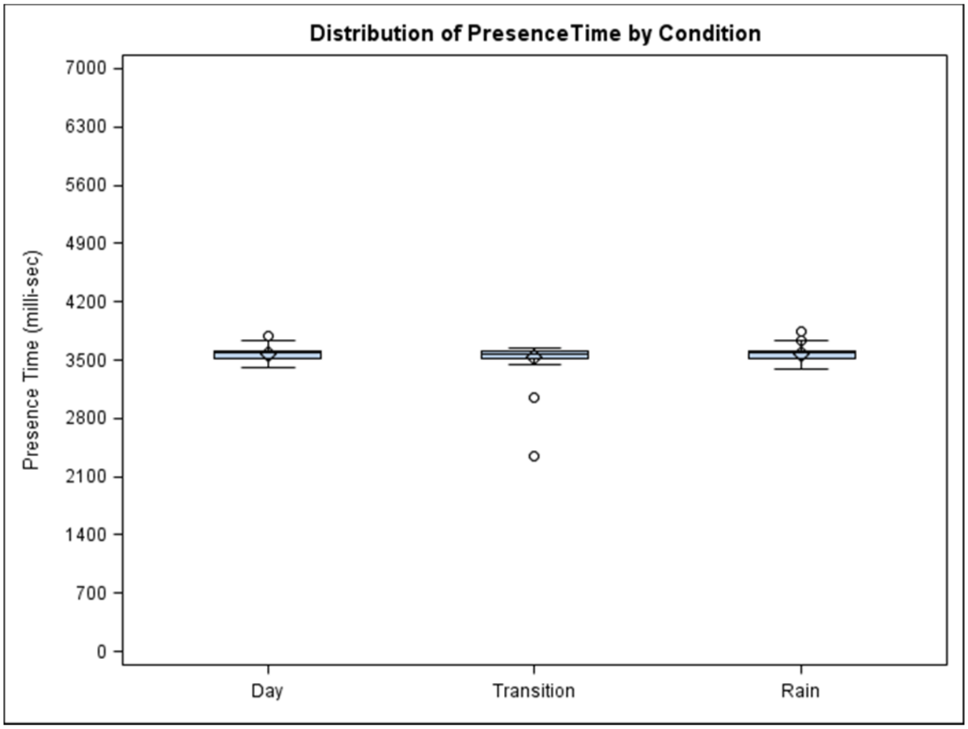


Figure 48. Box Plots of Presence Time by Iteris (SB 15) Upstream.

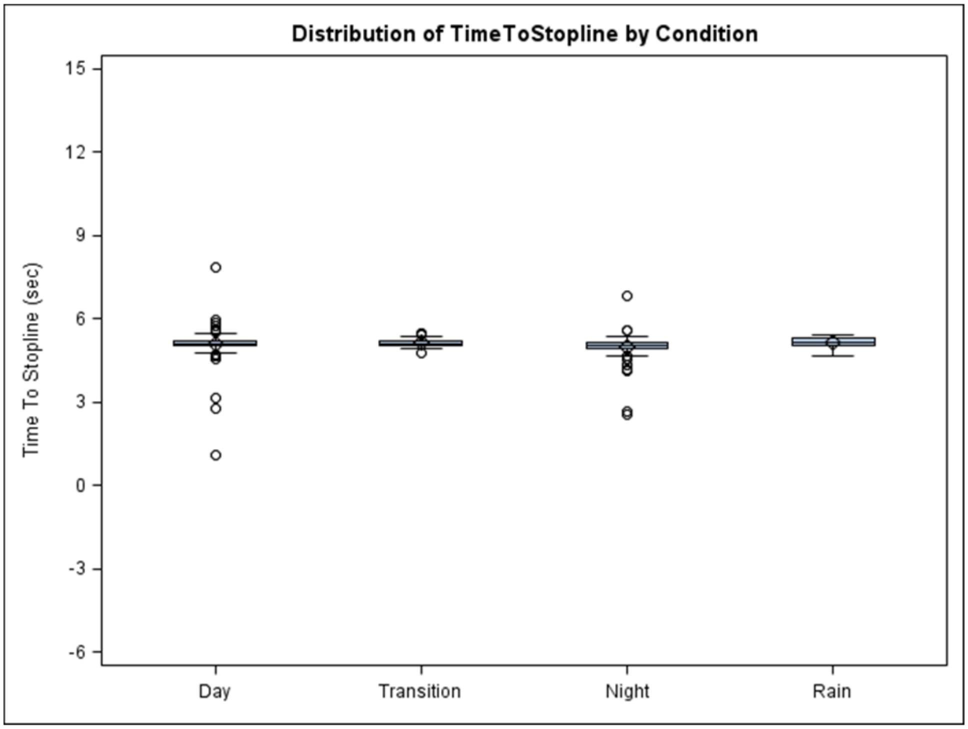


Figure 49. Box Plots of the Time to Stop Line when the Wavetronix Advance (SB 21) Turned On.

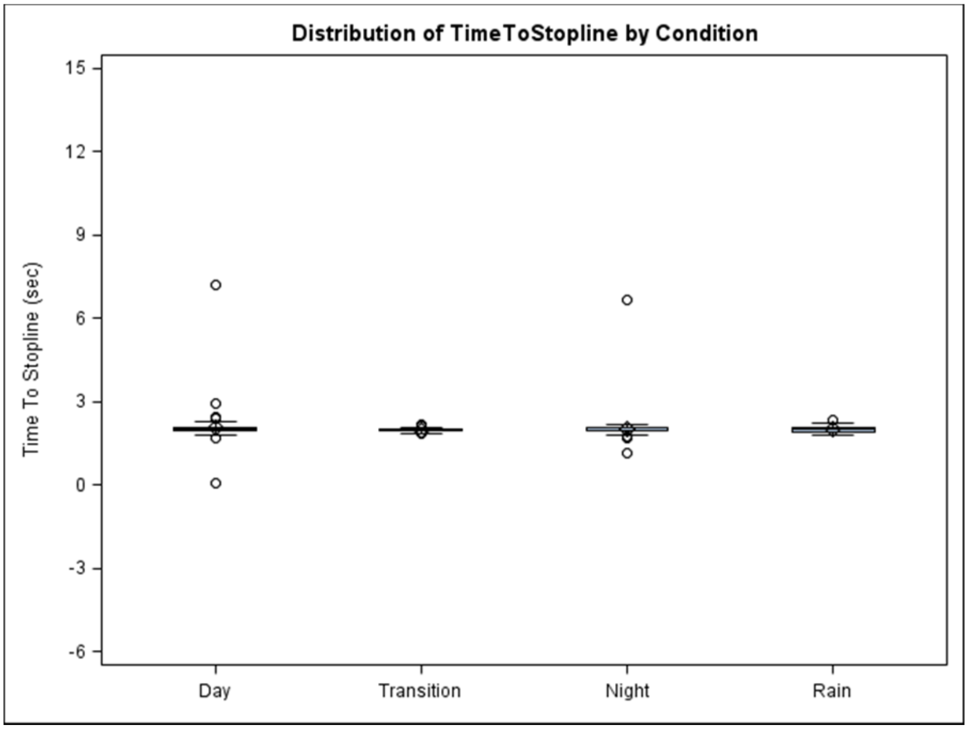


Figure 50. Box Plots of the Time to Stop Line when the Wavetronix Advance (SB 21) Turned Off.

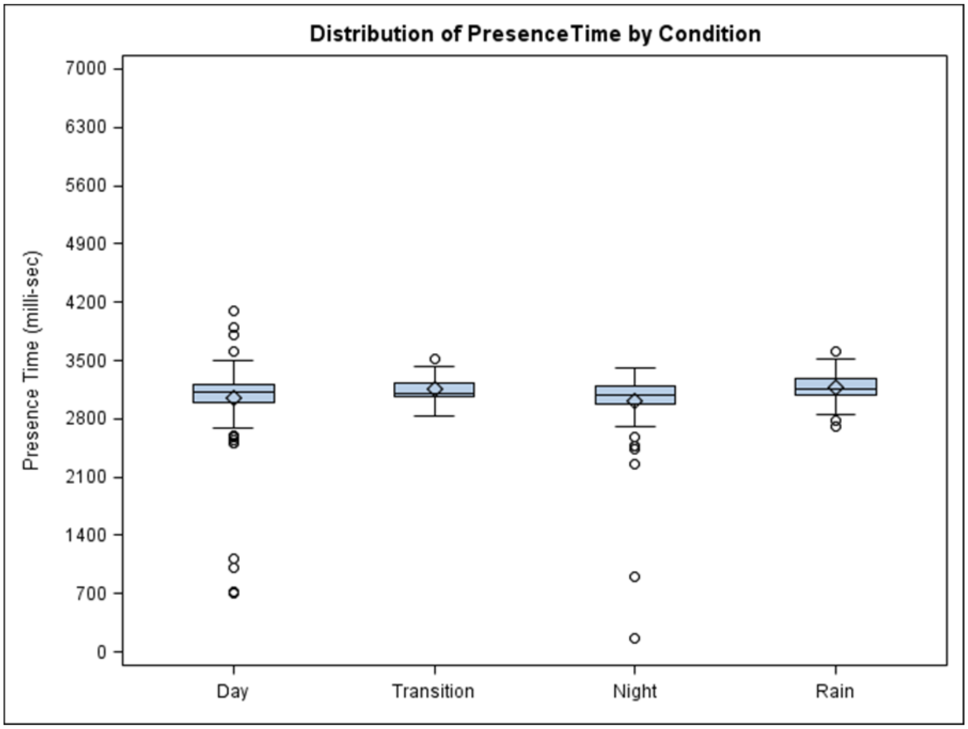


Figure 51. Box Plots of Presence Time by Wavetronix Advance (SB 21) Upstream.

Table 25. Boxplot Data Summary for Aldis GridSmart (SB38,SB46).

Test Speed	Condition	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
Upstream									
50	Day, Dry	SB38	722	2.98	2.84	713	5.14	2.95	2.16
70	Day, Dry	SB38	227	1.65	1.31	225	3.67	1.79	2.02
50	Trans, Dry	SB38	113	3.52	1.88	113	6.56	2.60	3.04
70	Trans, Dry	SB38	110	1.09	3.25	108	1.46	3.44	0.37
50	Night, Dry	SB38	90	3.85	0.16	89	8.31	0.28	4.46
70	Night, Dry	SB38	180	2.52	0.08	177	5.77	0.12	3.25
50	Day, Rain	SB38	393	2.63	2.93	396	4.71	3.65	2.08
70	Day, Rain	SB38	75	1.48	1.47	76	3.22	1.47	1.74
Stop Line									
50	Day, Dry	SB46	481	-1.42	1.19	481	0.43	1.17	1.84
70	Day, Dry	SB46	361	-1.24	0.32	361	0.24	0.38	1.48
50	Trans, Dry	SB46	104	-1.42	0.57	105	0.54	0.46	1.96
70	Trans, Dry	SB46	33	-1.00	0.08	33	0.33	0.07	1.33
50	Night, Dry	SB46	212	-1.10	0.71	213	0.87	0.14	1.97
70	Night, Dry	SB46	176	-1.12	0.08	176	0.40	0.08	1.52
50	Day, Rain	SB46	235	-1.37	0.93	233	0.68	0.51	2.05
70	Day, Rain	SB46	68	-1.11	0.09	68	0.45	0.13	1.56

Table 26. Boxplot Data Summary for FLIR VIP with IR Camera (SB5).

Test Speed	Condition	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	Day, Dry	366	-0.81	0.18	367	-0.27	0.09	0.54
70	Day, Dry	261	-0.77	0.18	263	-0.29	0.07	0.48
50	Trans, Dry	44	-0.75	0.08	44	-0.26	0.07	0.49
50	Night, Dry	211	-0.74	0.49	212	-0.23	0.38	0.51
70	Night, Dry	176	-0.72	0.60	178	-0.25	0.51	0.47
50	Day, Rain	168	-1.00	0.59	169	-0.26	0.10	0.74
70	Day, Rain	65	-0.98	0.73	65	-0.28	0.20	0.70

Table 27. Boxplot Data Summary for Iteris Vantage Vector (SB13) at Stop Line.

Test Speed	Condition	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	Day, Dry	191	2.73	0.15	189	6.27	0.69	3.54
70	Day, Dry	52	-0.66	0.16	53	-0.12	0.06	0.54
50	Trans, Dry	29	-0.71	0.07	29	-0.09	0.06	0.62
70	Trans, Dry	33	-0.59	0.06	33	-0.15	0.04	0.44
50	Day, Rain	30	-0.77	0.10	31	-0.11	0.16	0.66

Table 28. Boxplot Data Summary for Iteris Vantage Vector (SB15, SB16) Upstream.

Test Speed	Channel	Condition	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	SB15	Day, Dry	191	2.73	0.15	189	6.27	0.69	3.54
70	SB15	Day, Dry	58	1.24	0.37	58	4.75	0.35	3.51
70	SB16	Day, Dry	26	1.75	0.15	26	5.25	0.12	3.50
50	SB15	Trans, Dry	29	2.51	0.11	29	6.06	0.27	3.54
70	SB15	Trans, Dry	25	0.76	0.10	24	4.28	0.14	3.52
70	SB16	Trans, Dry	24	1.57	0.13	24	5.07	0.12	3.50
50	SB15	Day, Rain	40	2.71	0.11	40	6.31	0.11	3.60
70	SB15	Day, Rain	23	0.83	0.09	23	4.37	0.07	3.54
70	SB16	Day, Rain	19	1.67	0.08	19	5.18	0.08	3.51

Table 29. Boxplot Data Summary for Wavetronix Matrix (SB17).

Test Speed	Condition	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	Day, Dry	75	-1.24	0.30	75	0.53	0.19	1.77
70	Day, Dry	73	-1.12	0.16	73	0.17	0.20	1.29
50	Trans, Dry	45	-1.22	0.19	45	0.45	0.23	1.67
50	Night, Dry	40	-1.16	0.15	40	0.54	0.21	1.69
70	Night, Dry	70	-1.11	0.16	70	0.16	0.20	1.28
50	Day, Rain	31	-1.08	0.42	31	0.50	0.20	1.59
70	Day, Rain	27	-1.05	0.12	27	0.21	0.24	1.26

Table 30. Boxplot Data Summary for Wavetronix Advance (SB21).

Test Speed	Condition	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	Day, Dry	78	2.11	0.60	77	5.20	0.45	3.09
70	Day, Dry	79	1.97	0.24	79	4.98	0.54	3.00
50	Trans, Dry	45	1.97	0.07	45	5.12	0.14	3.15
50	Night, Dry	40	1.99	0.09	40	5.12	0.18	3.13
70	Night, Dry	74	2.03	0.56	76	4.95	0.49	2.92
50	Day, Rain	29	2.02	0.10	29	5.20	0.18	3.18
70	Day, Rain	30	1.98	0.11	30	5.14	0.15	3.16

GPS Results at Riverside

Table 31 summarizes the outcome of the GPS data collection with more information available in Appendix E. The original intent for using GPS was to serve as ground truth for test detectors that continuously monitor vehicle speed and distance. Two issues introduced apprehensions about this approach: 1) the accuracy of GPS for determining position accuracy, and 2) only being able to instrument one vehicle. Researchers realized during initial tests that Trafficware Pods positioned along the runway at know spacings would solve both issues. The research team collected GPS data anyway since it could still be used as ground truth for presence detection accuracy and rely on the Pods for positional accuracy.

Table 31. Riverside Detection Rates Based upon GPS Results. [a]

Detector and Controller Channel	Description	50 mph			70 mph		
		Clear Day	Clear Night	Rain Day	Clear Day	Clear Night	Rain Day
FLIR SB5	FLIR VIP Stop Line	1.00	1.00	0.98	1.00	1.00	0.93
Iteris SB13	Stop Line	0.99	0.98	0.90	0.97	1.00	#N/A
Iteris SB15	Trip Line at 485 ft	1.00	0.98	0.96	1.00	1.00	1.00
Iteris SB16	Trip Line at 566 ft	#N/A	#N/A	#N/A	1.00	#N/A	1.00
Wavetronix SB17	SmartSensor Matrix	1.01	#N/A	1.00	1.00	1.00	1.00
Wavetronix SB21	SmartSensor Advance	1.00	#N/A	1.00	1.00	1.00	1.00
Aldis SB38	Southbound Upstream	1.31	0.94	1.17	1.36	0.99	0.96
Aldis SB46	Southbound Stop Line	0.88	1.00	1.00	0.92	0.89	0.96
Pod SB59	At Stop Line	1.00	0.99	1.00	1.00	1.00	1.00
Pod SB51	100 ft from Stop Line	1.00	1.00	1.00	0.99	1.00	1.00
Pod SB52	200 ft from Stop Line	1.00	1.00	1.00	1.00	1.00	1.00
Pod SB53	300 ft from Stop Line	1.00	1.00	1.00	1.00	1.00	1.00
Pod SB54	400 ft from Stop Line	0.99	0.99	1.00	0.98	1.00	1.00
Pod SB55	500 ft from Stop Line	0.99	1.00	1.00	0.99	1.00	1.00
Pod SB56	600 ft from Stop Line	1.00	1.00	1.00	1.00	1.00	1.00
Pod SB57	700 ft from Stop Line	0.99	0.97	1.00	1.00	0.99	0.98
Pod SB58	800 ft from Stop Line	0.99	0.95	1.00	1.00	0.99	1.00

[a] Shaded cells indicate unusually high or low values.

In an ideal run of the single GPS vehicle, one run should produce one on and one off detector event for each detector. If a run did not register a detection event, the result is considered a missed call. False calls happen when a single run registers more than one on or one off event. Detection rates are calculated as the ratios of the number of detection events to the number of GPS runs. Results greater than 1.0 imply false calls, whereas results less than 1.0 imply missed calls. Stuck-on calls and dropped calls are based on Pod results, so they are not tabulated in this section. Table 31 summarizes presence detection rates from the GPS test runs, indicating unusually high or low values by shading.

The researchers also examined the precision of detections in terms of the consistency of the detector activation and deactivation using the GPS results alone. Figure 52 shows GPS box-and-whisker plots of the vehicle's distance to the stop line during clear daytime at 70 mph. Figure 53 shows the GPS box plots of the vehicle's travel time to the stop line for the same test conditions. The travel time to the stop bar is calculated from the instantaneous speed readings from GPS at the moment of the detector events. As noted earlier for detector box plots, a smaller box indicates better detection precision (high consistency), and a larger box shows the opposite. The data points outside the whiskers indicate potential outliers. Of note in this case are the outliers for the Aldis advance detector (SB38). This result comes from detections that intermittently come on and off as vehicles approach the stop line (false calls).

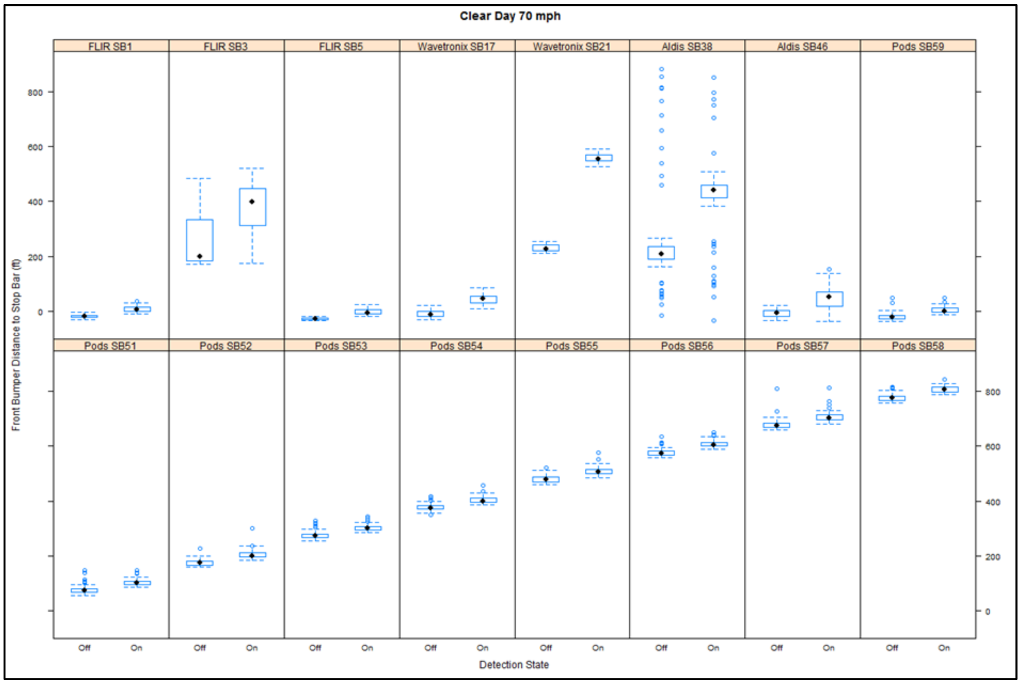


Figure 52. GPS Box Plots of Travel Distance to Stop Bar at On/Off Detections.

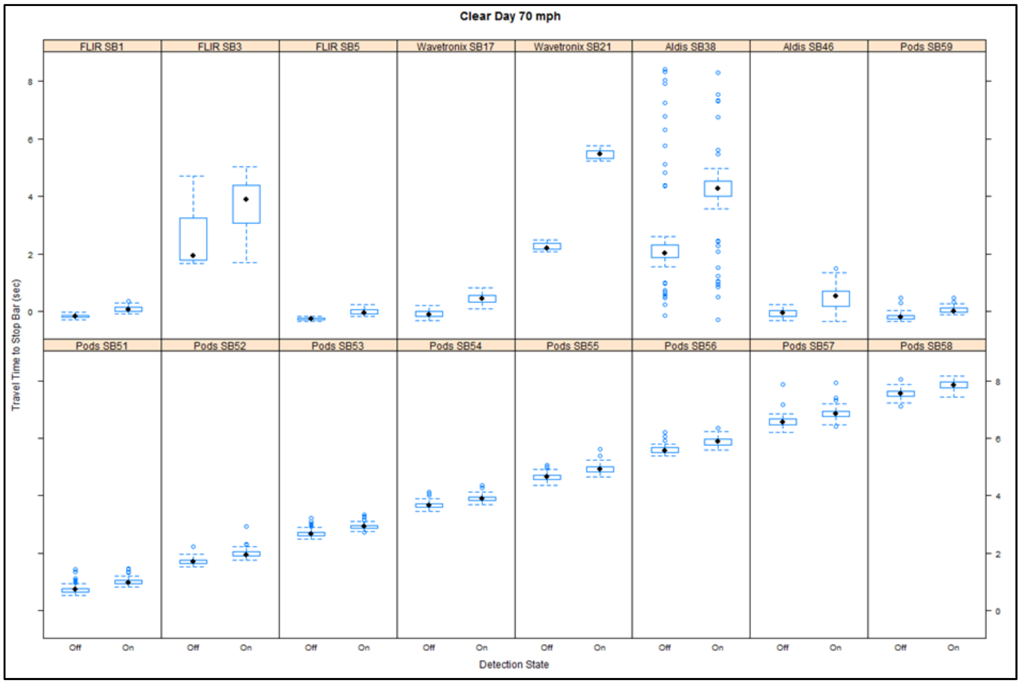


Figure 53. GPS Box Plots of Travel Time to Stop Bar at On/Off Detections.

INTERSECTION RESULTS

Due to the tight project schedule and the process required to collect and ground truth data at the four intersections, this project could not collect and process as much data as was the case during the earlier TAMU Riverside data collection. For those reasons, most or all of the following analyses should be considered as observations instead of more desirable full-scale scientific findings. For each site, the research team used recorded video as ground truth. The researchers started the data collection activity by contacting the detector manufacturers to identify sites and schedule a trip to the site to ensure optimum operation. In all cases but one, each manufacturer participated by traveling to the site and checking their equipment. The exception was the Austin site (FM 973/FM 969) where TxDOT had installed Trafficware Pods.

Austin District: FM 973/FM 969

Trafficware Pods

Table 32 summarizes the Trafficware magnetometer results at this intersection for the period beginning at 11:43 a.m. and ending at 3:25 p.m. The weather was dry and partly cloudy for the entire period. Compared to recorded video as ground truth, there were six instances when a trailer with high ground clearance failed to be detected on Channel 11 and two similar trailers that were not detected on Channel 12. With passage of a combination vehicle (tractor-semitrailer), the data recorded at the controller usually indicated that the channel activated when the tractor was over the first detector but turned off when the trailer was over that detector. Even though this phenomenon might not cause errors in the vehicle count, it would result in incorrect presence time. The number of combination trucks during the 11:43 a.m. count period with only partial detection was six occurrences out of 22 trucks, or 27.3 percent, and three occurrences out of nine trucks, or 33.3 percent, during the 1:36 p.m. period.

Table 32. Trafficware Magnetometer Results FM 973/FM 969.

Channel	Location	Correct Detections	Missed Calls	False Calls	Dropped Calls	Stuck-On Calls
3	Stop Line	101	2	0	1	0
4	Stop Line	100	1	0	2	0
11	Upstream	329	17	8	-	-
12	Upstream	167	16	2	-	-

Austin District: RM 1431/Mayfield Ranch

Iteris Vantage Vector

Table 33 shows the Iteris Vantage Vector tripline design values for design speeds ranging from 40 mph to 55 mph. This setup was different from the one used at Riverside since the earlier firmware only offered two triplines. As an example of how these values would be used when the intersection is not in coordination mode and at a design speed of 55 mph or higher, the installer would create triplines (arranged far to near: TL3, then TL2, then TL1) at 484 ft, 444 ft, and 314 ft (see Table 34). Speeds at or greater than 55 mph should trigger each detector in turn and cause an extension in the controller of 1.8 sec with each actuation as long as the vehicle speed did not drop to less than 50 mph once it passed TL3 and until the controller reaches its MAX GREEN setting.

Table 33. Iteris Vantage Vector Tripline Design Values.

Design Speed	TL1		TL2		TL3		Extension (sec)
	Distance	Speed	Distance	Speed	Distance	Speed	
55	314	50	444	50	484	55	1.8
50	284	45	403	45	444	50	1.8
45	255	40	363	40	403	45	1.8
40	225	35	323	35	363	40	1.8

Table 34. Iteris Channel Assignments at RM 1431/Mayfield Ranch Blvd.

Channel	Distance from Stop Line	Tripline Assignment
14	484 ft	SB14
15	444 ft	SB15
16	314 ft	SB16

The following Iteris Vantage Vector observations come from comparing isolated eastbound vehicles on RM 1431 approaching the intersection during periods when the intersection was not in coordination mode. The three detectors (far to near) were connected to controller channels SB14, SB15, and SB16. Therefore, any vehicle traveling 55 mph or faster should trigger all three detectors and generate extensions of 1.8 sec at the respective channels. The initial observations used the time interval from 4:00 a.m. to 5:00 a.m. The results based on observing 28 isolated vehicles over this one-hour period are as follows:

- Several vehicles only extended the call for one or two of the three total detectors, but only two of these instances can be explained by the vehicle going too slow. For the rest of the cases, the vehicle in question was the only one passing over the triplines and was going fast enough to extend the call for the other detector(s).
- Nineteen vehicles turned on all three detectors; all were traveling faster than 55 mph.
- Five vehicles turned on SB15 and SB16 (but not SB14); one was traveling slower than 54 mph, one at 55 mph, and three were faster than 55 mph.
- Three vehicles turned on only SB16; all were traveling faster than 55 mph.
- One vehicle turned on only SB15 (but not SB14 or SB16); this vehicle was traveling at 56 mph.

Wavetronix Advance (SS-200E)

Table 35 provides summary statistics of Wavetronix truck data obtained in Austin using a sample of 20 trucks observed during nighttime hours on August 9 and 10, 2015. Vehicle classification accuracy as truck or non-truck by the Advance SS-200E was low but it erred on the safe side by providing extra clearance time to non-trucks. It classified six trucks as non-trucks and classified 10 non-trucks as trucks. The last column in the table shows the design values.

Table 35. Wavetronix Truck Data Summary.

Variable	**Statistic**				**Design Value**
	Mean	**SD**	**Min**	**Max**	
Discovery distance (ft)	860.4	1.34	860	865	860
Distance at T1 (ft)	1.3	99.8	393	757	--
Time to stop line from T1 (secs)	7.43	1.11	4.54	10.1	7.5
Distance at T2 (ft)	157.9	51.1	48	228	--
Time to stop line from T2 (secs)	1.93	0.54	0.61	2.33	2.5
Presence time (secs)	5.50	1.48	2.50	8.0	5.0

The analysis conducted a one-sided *t*-test to compare the mean of obtained variables to design values. For the discovery distance, the obtained *t*-value from the *t*-test is 1.00 with a *p*-value of 0.3356. This finding suggests that the null hypothesis cannot be rejected and thus the mean of the discovery distance obtained from the sample is not significantly different from the design value of 860 ft. For the time to stop line from T1, the obtained *t*-value for the test against 7.5 sec is −0.23 with a *p*-value of 0.8202. Thus, the sample mean is not significantly different from the design value of 7.5 sec. For the time to stop line from T2, the *t*-value is −3.98 and the *p*-value is 0.0016. This result suggests that the time from T2 is significantly different from the design value of 2.5 sec. The two-sided *t*-test results suggest that the mean of the time to stop line from T2 is significantly lower than 2.5 sec. The design value for the presence time is 5.0 sec. The obtained *t*-value and *p*-value from the one-sided *t*-test are 1.26 and 0.231, respectively, which means that the null hypothesis cannot be rejected and thus the mean of the sample data is not significantly different from 5.0 sec.

To summarize, the previously stated objectives for the Wavetronix Advance in this test were to: a) determine its accuracy in detecting trucks vs. non-trucks, and b) determine how much controller extension time it provided for vehicles it classified as trucks (and non-trucks). Again, Twincrest set 2.5 to 7.5 sec for trucks and 2.5 to 5.5 sec for non-trucks. Except for the T2 value being lower than 2.5 sec (statistically different), the second objective was met. A larger sample might find different results for classification of trucks.

Wavetronix Matrix

Part of the Wavetronix Matrix results are based on recorded video for two daylight time periods—9:55 a.m. to 10:55 a.m. and 2:00 p.m. to 3:00 p.m.—when traffic was heavy and there were no weather factors that might influence radar detector performance. The number of stuck-on calls for these two one-hour periods was greater than expected during both hours. One factor that might have influenced these calls was the presence of one or more vehicles stopped in the left turn lane.

During another observation period beginning in the late afternoon at 8:25 p.m. and ending at 9:25 p.m., daylight transitioned to darkness, although light conditions should not affect radar performance. The number of calls at the stop line for this time interval was about the same as during the earlier period during full daylight. Table 36 summarizes the results for all three periods. The third observation period showed no indication of stuck-on calls.

Table 36. Wavetronix Matrix Results from RM 1431/Mayfield Ranch Blvd.

Time Period	Correct Detections	Missed Calls	False Calls	Dropped Calls	Stuck Calls	Total Calls	% Correct
9:55 a.m. to 10:55 a.m.	273	1	3	0	19	296	92.2%
2:00 p.m. to 3:00 p.m.	265	0	1	0	24	290	91.4%
8:25 p.m. to 9:25 p.m.	284	1	0	0	0	285	99.6%

Houston District: FM 2920/Hannover Woods

Aldis GridSmart

Table 37 and Table 38 summarize the Aldis GridSmart observations for two hours at night and two hours in the daytime, respectively. The following observations pertain to the Aldis GridSmart's performance near the stop line:

- All of the Phase 6 missed calls happened in the right lane, and most of the missed calls were vehicles traveling at a relatively high speed.
- Most of the Phase 5 false calls were caused by trucks traveling in the adjacent lane but counted by the Phase 5 detector. In some instances, when the truck had moved beyond the Phase 5 detection zone, the Phase 5 detector would turn off even when another vehicle still occupied the Phase 5 detection zone.

Table 37. Aldis GridSmart Nighttime Results FM 2920 (9:00 p.m. to 11:00 p.m.)

Signal Phase	Controller Channel	Correct Detections	Missed Calls	False Calls	Dropped Calls	Stuck-On Calls
2	36	429	0	1	0	1
6	38	524	10	0	0	3
5	35	44	3	6	0	0
1	37	6	0	1	0	0
	Total	1003	13	8	0	4

Table 38. Aldis GridSmart Daytime Results FM 2920 (9:00 a.m. to 11:00 a.m.)

Signal Phase	Controller Channel	Correct Detections	Missed Calls	False Calls	Dropped Calls	Stuck-On Calls
2	36	345	0	6	0	1
6	38	835	25	4	0	0
5	35	67	1	48	0	0
1	37	15	0	15	0	0
	Total	1262	26	73	0	1

Houston District: FM 1488/Kuykendall Boulevard

Table 39 and Table 40 summarize results from comparing the FLIR VIP using an infrared camera with recorded video at FM 1488/Kuykendall Boulevard in north Houston in the area of Spring, Texas. Detectors 1 and 2 are the stop line detectors, and detectors 3 and 4 are upstream detectors on the same approach. Table 39 shows the daytime data starting at 2:16 p.m. and ending at 3:22 p.m., and Table 40 shows nighttime data starting at 9:16 p.m. and ending at 10:17 p.m. The most troubling finding during the daytime results is missed calls upstream of the intersection. This finding suggests that infrared camera detection systems may have problems detecting vehicles during daylight in hot weather, perhaps due to lack of heat contrast between vehicles and their background. Based on the data collected, the upstream detection was better at night, while detection at the stop line was similar during daytime and nighttime. The analyst did not observe any false detections or stuck-on calls.

Table 39. FLIR VIP with IR Camera Daytime Results at FM1488/Kuykendall.

Detector	Description	Correct Detections	Missed Calls	False Calls	Dropped Calls	Stuck-On Calls
1	Stop Line	341	1	0	0	0
2	Stop Line	365	2	0	0	0
3	Upstream	132	25	0	0	0
4	Upstream	134	36	0	0	0
	Total	972	64	0	0	0

Table 40. FLIR VIP with IR Camera Nighttime Results at FM1488/Kuykendall.

Detector	Description	Correct Detections	Missed Calls	False Calls	Dropped Calls	Stuck-On Calls
1	Stop Line	168	0	0	0	0
2	Stop Line	136	1	0	0	0
3	Upstream	175	5	0	0	0
4	Upstream	141	1	0	0	0
	Total	620	7	0	0	0

CHAPTER 6. GUIDELINES FOR NEW VEHICLE DETECTORS

INTRODUCTION

Based on initial data collected at Riverside under controlled conditions for seven relatively new and untested detectors, all but one performed well enough to continue testing both at Riverside and at TxDOT intersections. All remaining detectors are worthy of further evaluation by TxDOT with certain caveats as discussed in this chapter. The guidelines contained herein are intended to assist TxDOT and other agencies in the selection and use of these newer detectors. The guidance provided in this chapter is intended to answer two questions:

- How does it work?
- How well does it work?

Due to time constraints and the inability to capture some of the desired environmental conditions within the research period, the following information is supplemented by pertinent information from the literature search as documented in Chapter 2. Even though literature information was limited pertaining to the selected detectors at the time of the search, there is still useful information for the guidelines. Summary results are segregated by stop line results and upstream results and are organized by Riverside results first followed by intersection results, and finally literature results.

SUMMARY OF RESEARCH FINDINGS

Detection at Stop Line

Aldis GridSmart at Stop Line

How does it work? The Aldis sends a call to the controller the instant it detects a vehicle and holds the call to the controller until no vehicles occupy the detection zone.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- Figure 39 box plots show presence time (mean value) is reasonably constant with mean values that range from 1800 to 2000 milliseconds across the four weather/light conditions.
- Figure 39 box plots show excessive outliers both above and below the mean values for day, dry and day, rain. The two center quartiles have relatively large spreads that reach as high as 0.5 sec.
- Table 23 correct detection rates ranged from 79.6 percent (50 mph, day, dry) to 100.0 percent (70 mph, all except day, dry).
- Table 24 shows that the Aldis missed 52.8 percent of the motorcycles at the stop line.

Intersection Results.

- Pertinent Findings: See Table 41.

Table 41. Aldis GridSmart Daytime and Nighttime Results FM 2920.

Signal Phase	Controller Channel	Correct Detections	Daytime		Nighttime	
			Missed Calls	False Calls	Missed Calls	False Calls
2	36	429	0	6	0	1
6	38	524	25	4	10	0
5	35	44	1	48	3	6
1	37	6	0	15	0	1
Total		1003	26	73	13	8

Literature Results.

- No literature results were available for the Aldis GridSmart.

FLIR VIP with IR Camera at Stop Line

How does it work? This system functions like other video systems but uses an infrared imager rather than a visible light camera.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- Figure 41 box plots of presence time indicate mean values for day, transition, and night were consistent at 0.5 sec, but outliers above the mean occurred for all except transition. Outliers exhibited a range from 1.0 to 5.0 sec.
- Table 23 indicates that all weather conditions yield similar results.
- Table 24 shows that the FLIR was 96.2 percent accurate for motorcycles.

Intersection Results.

- Table 42 indicates the detection performance. Missed, dropped, false, and stuck-on calls were all negligible.

Table 42. FLIR VIP with IR Camera Daytime and Nighttime Stop Line Results at FM 1488/Kuykendall.

Detector	Description	Correct Detections	Daytime		Nighttime	
			Missed Calls	False Calls	Missed Calls	False Calls
1	Stop Line	341	1	0	0	0
2	Stop Line	365	2	0	1	0
Total		706	3	0	1	0

Literature Results.

- Grossman et al. compared traditional video camera activation times daytime versus nighttime and found a 1-sec difference.
- Thermal cameras resulted in negligible differences in activation times day to night (*30*).

Iteris Vantage Vector at Stop Line

How does it work? The Iteris detector uses traditional video detection for the stop line area so it should detect a vehicle as it enters the detection zone and hold the call until no vehicles occupy the zone.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- Figure 40 box plots of presence time by Iteris indicate fluctuating mean values from 0.5 sec to 1.5 sec but the two central quartiles reasonably consistent for day, transition, and rain.
- Table 23 indicates poor results for 70 mph runs during rain.
- Table 24 indicates that the Iteris stop line camera missed all 25 motorcycles.

Intersection Results.

- No intersection results were available from the Austin site due to controller limitations.

Literature Results.

- The literature search did not find any results on the Iteris Vantage Vector.

Trafficware Pods at Stop Line

How does it work? Magnetometers passively monitor the earth's magnetic field and detect a vehicle passing by detecting changes in the magnetic flux lines.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- Table 23 indicates Pod performance at Riverside was lowest at day, dry, 50 mph (mean 90.0 percent) and highest at day, transition, 70 mph (mean 99.7 percent).
- In six out of all eight possible combinations Pods were 95 percent or better and the Pod overall mean value for all conditions was 94.6 percent.

Intersection Results.

- Correct detections at the stop line at the Austin intersection were 101 of 104 (97.1 percent) and 100 of 103 (97.1 percent).
- For two upstream detection areas the Pods correctly detected 329 of 354 (92.9 percent) and 167 out of 185 (90.3 percent).
- The most prevalent error type was missed calls and they were more common upstream than at the stop line. Missed calls and dropped calls at the stop line were only 3 percent of the total, whereas missed calls upstream were 6.1 percent.

Literature Results.

- The literature search did not find any evaluations of the Trafficware Pods.

Wavetronix Matrix at Stop Line

How does it work? The Matrix is a stop line detection system that uses a patented radar imaging process to monitor all vehicles, moving or stopped, in up to 10 lanes of traffic.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- Table 23 shows 50 mph results are excellent, ranging from 97.6 percent to 106.9 percent. Results at 70 mph dropped to 90.0 percent to 97.9 percent.
- Figure 42 box plots of presence time at the stop line indicate mean values consistently ranging from 1300 to 1600 milliseconds for all light/weather conditions.
- Figure 42 box plots show the two central quartiles are consistent at about 0.5 sec duration. Outliers are negligible.
- Table 24 indicates that the Matrix detected 100 percent of motorcycles at the stop line.

Intersection Results.

- The number of stuck-on calls in two of three observation intervals (19 of 273 [7.0 percent], and 24 of 265 [9.1 percent]) was greater than expected.
- Stationary left-turn vehicles might have influenced these stuck-on calls. Misses and false calls were negligible.

Literature Results.

- Wavetronix tested its SmartSensor Matrix detector near the stop line and found presence detection accuracies in the range of 72.0 percent to 86.8 percent.
- Another Wavetronix test at 45 mph using count zones placed back from the stop line found a count accuracy of 92.6 percent.
- Another Wavetronix mid-block test at 45 mph resulted in a count accuracy of 99.7 percent (*33*).

- Medina et al. tested the Matrix under the following weather conditions: normal, wind, snow, and rain. Resulting error rate percentages (false, missed, stuck-on, and dropped calls for the last three categories were negligible, but for false calls in snow the error rates were 48 percent and in rain 7 percent.

Detection Upstream

Aldis GridSmart Upstream

How does it work? The Aldis sends a call to the controller the instant it detects a vehicle and holds the call to the controller until no vehicles occupy the detection zone. Upstream detection zone was at 400–450 ft.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- Figure 43 box plots indicate that the mean travel times upon entering the detection zone range from about 4.0 sec to 7.0 sec for all conditions but with high variability.
- Figure 44 box plots of the time to stop line when the Aldis turned off indicate mean travel times reasonably consistent at 3.0 sec in all conditions but with numerous outliers in day, dry and day, rain.
- Table 23 results show that correct detections ranged from 67.8 percent to 98.9 percent at 50 mph and from zero percent to 100.0 percent at 70 mph.
- Table 24 shows the motorcycle detection accuracy to be 11.3 percent.

Intersection Results.

- TTI was unable to use the intersection data collected with the Aldis rectilinear camera at the Houston intersection of FM 2920/Hannover Woods Blvd.

Literature Results.

- The literature search did not produce anything on the performance of this detector.

FLIR VIP with IR Camera Upstream

How does it work? This system functions like other video systems but uses an infrared imager rather than a visible light camera. The infrared camera provided by FLIR did not have the appropriate optics to cover both the stop line and the upstream area at Riverside. Therefore, the installation crew installed it to cover only the stop line.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections, and supplemented by literature sources.

Riverside Results.

- The optics of the camera would only allow coverage at the stop line so no upstream results are available.

Intersection Results.

- Table 43 summarizes the upstream results for the infrared camera system, indicating less than desirable results during the daytime but excellent results at night. All of these errors were missed calls.

Table 43. FLIR VIP with IR Camera Daytime and Nighttime Results Upstream at FM 1488/Kuykendall.

Detector	Description	Correct Detections	Daytime		Nighttime	
			Missed Calls	False Calls	Missed Calls	False Calls
3	Upstream	132	25	0	5	0
4	Upstream	134	36	0	1	0
Total		266	61	0	6	0

Literature Results.

- Iwasaki et al. developed two algorithms, one to detect vehicles' windshields and the second to detect thermal energy generated by vehicle tires. The second one had a false-call rate of 3.4 percent and a missed-call rate of 7.2 percent. No information was provided as to the availability of the algorithm to state DOTs (*39*).

Iteris Vantage Vector Upstream

How does it work? Using Doppler radar, the detector tested at Riverside used two triplines, which was a predecessor to the three tripline scheme used for the Austin data.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- The two triplines were connected to controller Channel 15 and Channel 16 as follows:
  - Channel 15: near tripline at 485 ft.
  - Channel 16: far tripline at 566 ft.
- Table 23 results indicate that the far trip line (566 ft) was most accurate (72.7 percent) during transition, dry, 70 mph; and worst (39.4 percent) during day, dry, 70 mph. Vehicle misses could potentially result in no indecision zone protection upon green termination.
- Table 23 results indicate that the near tripline (485 ft) had its best results (95.2 percent) at day, rain, 50 mph and worst 79.0 percent) at day, dry, 50 mph. Vehicle misses could potentially result in no indecision zone protection upon green termination

- Figure 48 box plots of the presence time from initial detection to stop line at near tripline shows mean values to be consistent with little variation at 3.5 sec.
- Table 24 indicates that the Iteris near tripline missed 64.3 percent of motorcycles.
- Table 28 mean value for on times for SB16 for 70 mph, rain was 5.18 sec.
- Table 28 on times were consistently 3.50 sec or slightly higher.

Intersection Results.

- The detector correctly detected 20 of 28 vehicles (71.4 percent) traveling faster than 55 mph. Four vehicles activated two of the three triplines (but were above 55 mph), and four vehicles triggered only one of the three (again, above 55 mph).

Literature Results.

- The literature search did not uncover any previous research.

Trafficware Pods Upstream

How does it work? Magnetometers passively monitor the earth's magnetic field and detect a vehicle passing by detecting changes in the magnetic flux lines.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- Table 23 indicates Pod performance at Riverside was lowest at day, dry, 50 mph (mean 90.0 percent) and highest at day, transition, 70 mph (mean 99.7 percent).
- In six out of all eight possible combinations Pods were 95 percent or better and the Pod overall mean value for all conditions was 94.6 percent.

Intersection Results.

- At the stop line, Pods correctly detected 329 of 354 (92.9 percent) and 167 out of 185 (90.3 percent).
- Missed calls and dropped calls at the stop line were only 3 percent of the total whereas missed calls upstream were 6.1 percent.

Literature Results.

- The literature search did not find any previous evaluations of the Pods either for stop line or upstream detection.

Wavetronix Advance (SS-200E) Upstream

How does it work? The Wavetronix Advance uses a patented and unique process to detect and track vehicles using Doppler radar and updates their positions and speeds every 100 milliseconds and uses a Time of Arrival concept. The user inputs upper and lower bounds of the desired travel time to the stop line, typically 2.5 to 5.5 sec for non-trucks and 2.5 to 7.5 sec for trucks.

How well does it work? The input below comes from data collected at the TAMU Riverside campus and TxDOT intersections and supplemented by literature sources.

Riverside Results.

- Figure 49 box plots of time to stop line when the detector turned on were consistent for all conditions (day, transition, night, and rain) with almost no variation and mean of 5.0 sec.
- Figure 50 box plots of time to stop line when the detector turned off were consistent for all conditions (day, transition, night, and rain) with almost no variation and mean of 2.0 sec.
- Figure 51 box plots of presence time show consistent values in the range of 2800 to 3000 milliseconds for all conditions (day, transition, night, and rain). The only conditions with a few outliers were day and night (not transition or rain).
- Table 24 shows the motorcycle accuracy at 100 percent for the Advance.
- Table 30 on and off mean values were lower than expected (2.5 to 5.5 sec) so validation is needed. In the interim, users can add 0.5 sec to recommended values.
- Table 30 total on time was at or above the desired 3.0 sec in all but one condition.

Intersection Results.

- The detector classified 20.0 percent of the trucks correctly in late night samples but it erred on the safe side by classifying multiple cars as trucks.
- The discovery distance for trucks was always at least the set value of 860 ft.
- The desired mean value for truck on-time (T1) was 7.5 sec and the measured mean value was 7.43 sec with standard deviation of 1.1 s.
- The desired mean value for truck off-time (T2) was 2.5 sec and the measured mean value was 1.9 sec with standard deviation of 0.5 sec.
- The desired presence time for trucks was 5.0 sec and the measured value was 5.5 sec with standard deviation of 1.5 sec.

Literature Results.

- Since research project 0-6828 did not experience a wide variety of weather conditions, this guide relies on earlier research by Medina et al. (*35,36,37*). That research did not use the SS-200E as used in this research, but their findings are still considered relevant (Table 44).
- Hurwitz et al. found that drivers experienced less difficulty deciding to stop or proceed under radar sensor control, and the rate of red-light running for the radar detector was better than point detectors but the difference was not statistically significant (*44*).

Table 44. Effects of Weather Conditions on Wavetronix Advance Detectors.

Sensor Type	Weather	Failure Rate, %, by Failure Type			
		False Call	Missed Call	Stuck-On Call	Dropped Call
	Normal	11	1	0	0
	Wind [a]	0	0	0	0
	Snow [a]	30	2	0	0
	Rain	17	1	0	0

[a] System performance might have suffered due to a combination of wind and snow.

- Sharma et al. also compared the SmartSensor Advance to point detectors on two approaches at a signalized intersection using four metrics to determine how well it performed. Performance under each metric is summarized below:
  - Distance error analysis
    - There was a systematic negative bias in the distance reported by the Advance in one direction, but a fixed correction could remedy the problem.
    - The effect of distance, speed, and acceleration on the position accuracy was within 5 ft for the operating range, which was acceptable.
    - The vehicle type affected the estimation accuracy. Larger vehicles are reported to be further away than their actual distances.
  - Speed error analysis
    - Speed error was low in both directions.
    - None of the speed-error causes had a significant impact on the accuracy. The speed error was within 2 mph for the operating range.
  - Call activation and deactivation performance
    - There were 45 errors per day in one direction during the control volume tests, but the other direction was acceptable.
    - The volume comparison against loops indicated a mean error of 340 vehicles per hour (vph) in one direction and 180 vph in the other.
  - Start distance
    - These results indicate that the Advance performed reasonably well for vehicle tracking. The fixed bias can be removed by tweaking the setup parameters.
- In summary, the Advance showed potential for improving both the safety and efficiency of dilemma zone protection compared to point detectors, but it needs improvement in its detection and tracking accuracy (*42*).

RECOMMENDATIONS FOR COMBINING TECHNOLOGIES

Before providing guidance on how best to use the six detectors selected in this research, this section addresses the individual technologies available for vehicle detection and provides a basic understanding of how they might be used together. Each technology and subsequently each detector using that technology has certain strengths and weaknesses. Understanding these characteristics is essential to achieving a safe and efficient signalized intersection.

The best technology combinations would consider the strength of one technology paired with the strength of another technology. Some technologies are better suited for upstream coverage and perhaps different technologies are better suited for use at the stop line. The selection criteria for the best pairing of technologies would include the following:

- Overall cost.
- Detection accuracy.
- Traffic interference during installation/maintenance.
- Flexibility in case traffic conditions change.

Table 45 indicates the authors' ratings for the three technologies included in this research using the above criteria. Non-intrusive technologies such as radar and video offer obvious advantages as long as they are applied to the correct location (i.e., stop line or upstream).

Table 45. Observations Related to Detection Technology.

Technology	Rating for Stop Line	Rating for Upstream
Radar	Acceptable	Excellent
Magnetometers	Acceptable	Acceptable
Video	Acceptable	Not recommended for high speeds

Video is more appropriate at the stop line than upstream. If an agency is willing to use intrusive technology, then wireless magnetometers would be acceptable either at the stop line or upstream. Radar is acceptable for either detection area as well but cost may be a factor in that decision. As noted earlier, combining technologies would realize the best outcome by drawing on the strengths of each individual technology.

Radar is considered to be the best technology overall for upstream detection. Even though wireless magnetometers are acceptable for upstream, they are inflexible in terms of being able to adjust to speed changes and they require traffic control for installation and maintenance.

For the stop line, the acceptable technologies are magnetometers, radar, and video. Being non-intrusive moves the favorability of radar and video ahead of magnetometers. Based on initial cost alone, video will likely be less expensive than radar although the life cycle cost of radar will likely win out over video. Two hybrid detectors are already available with video for stop line monitoring and radar for upstream.

Quick Reference Guide

Table 46 and Table 47 are intended to provide a Quick Reference Guide for Practitioners on strengths/weaknesses of various detectors tested. Table 46 contains input for users when contemplating new detectors at the stop line for high-speed signalized intersections, and Table 47 has similar information for detection upstream at high-speed signalized intersections. Tabulated strengths and weaknesses serve as input to the guidelines provided later.

Ratings for strengths and weaknesses in these two tables are basically defined as above or below the average for the characteristic being evaluated. In this case, average means the generally acceptable range for a particular technology or even for another competing technology. Since this research did not conduct an in-depth cost comparison, the cost entries are based on the experience of the research team. Initial costs are readily available but the more important lift-cycle cost requires accurate historical data which is more difficult to acquire. In many cases a higher initial cost is offset by lower maintenance, resulting in the same or lower life-cycle cost compared to competing technologies. A good example is radar, which sometimes has a higher initial cost.

Table 46. Quick Reference for Stop Line Detectors.

Detection System	Strengths	Weaknesses
1.Aldis GridSmart	Single camera for all approaches Single CAT5 cable to camera Convenient video recording Optional turning movement counts	Camera location is critical Video is subject to weather/light conditions Camera maintenance
2. FLIR VIP w/IR Camera	Nighttime and some inclement weather detection improved	Higher cost of IR camera Video is still subject to some light and weather conditions
3. Iteris Vantage Vector	Lower cost than some options One installation point for two detectors	Video is subject to some light and weather conditions
4. Trafficware Pods	Quicker to install than loops Cost competitive with loops Presence detection excellent Not affected by weather/light	Intrusive requiring traffic control Latency of presence on
5. Wavetronix SS Advance (SS-200E)	N/A	N/A
6. Wavetronix SS Matrix	Radar immune to most weather One detector covers 10 lanes	Higher initial cost High stuck-on call rate High false calls during snowfall

Table 47. Quick Reference for Upstream Detectors.

Detection System	Strengths	Weaknesses
1.Aldis GridSmart	Single CAT5 cable to camera Convenient video recording	High false call rate upstream Camera maintenance
2. FLIR VIP w/IR Camera	Nighttime and some inclement weather detection improved	Missed calls mid-day hot weather Higher cost of IR camera
3. Iteris Vantage Vector	Radar immune to most weather Small footprint for 2 detectors	May be inappropriate for highest speeds
4. Trafficware Pods	Quicker to install than loops Cost competitive with loops Presence detection excellent Not affected by weather/light	Intrusive requiring traffic control Detection latency but user can compensate
5. Wavetronix SS Advance (SS-200E)	Patented Time of Arrival concept Longest detection range for high-speeds Radar immune to most weather Accurate dilemma zone detector	Limited classification accuracy
6. Wavetronix SS Matrix	N/A	N/A

DETECTOR GUIDELINES

The following guidelines for installation of the six new vehicle detectors assume that the installer has already considered the appropriate manufacturer's recommendations for installation of their system. Intersection data collection in this project was limited so further evaluation in subsequent research is essential. The following guidance will assist TxDOT with both choosing the most appropriate detector and once selected optimize its performance. The following material organizes detectors alphabetically then provides guidance by stop line first followed by upstream applications.

The guidance is predicated on technology selection since starting with the best technology ensures better overall performance. Since traffic signals on high-speed roadways are expected to operate reasonably well in all weather and light conditions, selection of suboptimal technologies that are sensitive to such conditions will result in detection errors that could lead to unsafe conditions.

Stop Line Guidance

Aldis GridSmart

- Camera placement is critical to satisfactory results; daytime false calls were high in left-turn lanes perhaps due to high profile vehicles.
- After installation, monitor performance in all traffic, weather, and light conditions to determine need for adjustments.
- Check activation times night versus day to determine need for adjustments.
- Excessive outliers could compromise intersection operational efficiency.

FLIR VIP with IR Camera

- This detector is recommended for stop line only, not for upstream detection.
- Consider an IR camera system only where weather and/or light artifacts will cause serious stop line detection issues with standard cameras.
- After installation, monitor performance in all traffic, weather, and light conditions to determine need for adjustments.
- Check vehicle activation times night versus day but IR camera will likely be the same for both conditions.
- Motorcycle detection was exceptional at 96.2 percent.

Iteris Vantage Vector

- This hybrid is an acceptable and cost-effective solution but not the best for high speeds.
- Mount and aim the video camera like any other video camera then monitor in all traffic, weather, and light conditions to determine need for adjustments.
- Check video activation times night versus day.
- Motorcycle detection was poor.

Trafficware Pods

- Pods are basically a loop replacement detector with similar characteristics as loops.
- Pods are not likely to be affected by most weather conditions although other research indicated potential compromise in wireless communication.
- Limit distance of Pods and the Access Point to manufacturer recommendations.
- Longitudinal spacing to replicate loops ≤ 12 ft for passenger cars.

- Check sensitivity settings and resulting accuracy using different vehicle types.
    - Motorcycles.
    - Detection of high-bed trucks.
    - Check adjacent lane detections.

Wavetronix SmartSensor Matrix

- Consider tall vehicles and possibility of false detections in adjacent lanes.
- Check the impact of stuck-on calls to determine their potential significance.
- Errors might increase in heavy rain and heavy snowfall but not likely in light to moderate conditions.
- Motorcycle detection is excellent.

Upstream Guidance

Aldis GridSmart

- Video is not recommended for upstream detection at high-speed intersections.
- If used, monitor performance in all traffic, weather, and light conditions.
- Check false call rate of Aldis upstream camera.
- Rain may affect performance so check during moderate to heavy rain.

FLIR VIP with IR Camera

- Video is not recommended for upstream detection at high-speed intersections.
- IR camera performance appeared to be worse than standard camera during daytime hot weather.
- Missed calls at nighttime were negligible, but in daytime misses were 15.4 percent and 21.0 percent.

Iteris Vantage Vector

- This hybrid detector is a cost-effective solution but not the best for high speeds.
- Missed detections were the most serious problem observed at both triplines at Riverside.
- Mount radar detector on the near side of the intersection to the approach it will monitor to optimize its range. This position requires the video camera to face the opposite direction.
- This detector is marginal for approaches with high truck volumes at or near 70 mph.
- The detector missed about two-thirds of motorcycles at 50 mph (not tested at 70 mph).
- The Vector provided adequate on times (off minus on) but its activation time was marginal during rain at 70 mph.
- The installer should test the detector at proposed intersections to determine its vehicle discovery distance to determine if adding time to the upper end of the range will provide sufficient protection at green termination.
- Errors in heavy rain and heavy snowfall might increase but not likely in light to moderate conditions.

Trafficware Pods

- Detection points for Pods will start with TxDOT inductive loop placement based on design speed and extension times.
- Exact Pod placement should consider latency of about 300 milliseconds before and after vehicles arrive over the Pod.
- Limit the distance to furthest Pod to not exceed manufacturer recommendations.

Wavetronix SmartSensor Advance (SS-200E)

- Set controller extension time to 1.0 sec.
- Low measured values of time of arrival of 2.0 to 5.0 sec need to be verified but in the interim the installer can increase the input values by 0.5 sec.
- Where feasible, mount the detector on the near side of the intersection.
- In research project 0-6828, many non-trucks were classified as trucks but these errors are not considered serious. Further research is needed.
- The installer should consider these findings during setup of a new intersection.
- Errors might increase in heavy rain and heavy snowfall but not likely in light to moderate conditions.

FUTURE RESEARCH

Some unanswered questions remain after completion of this research project. Many weather and lighting conditions were not available for testing during this project period. Testing at TxDOT intersections, while helpful, was limited in terms of how much data could be analyzed within the resources available. Future research needs to collect larger samples of data during a variety of weather and light conditions and traffic consisting of all vehicle types. Specific needs based on this research includes:

- Check Aldis activation times night versus day.
- Check Iteris stop line activation times night versus day.
- Verify false call rate of Aldis upstream camera.
- Verify IR camera performance during daytime hot weather.
- Verify time of arrival by Wavetronix Advance of 2.0 to 5.0 sec or the installer can increase the input values by 0.5 sec.
- Verify classification of trucks versus non-trucks of Wavetronix Advance (SS-200E).

APPENDIX A. PERTINENT RIVERSIDE EVENTS

INTRODUCTION

The following series of dates and events present a chronological sequence of activities that are pertinent to accomplishing the objectives of this research project. All of the early events pertain directly to installing equipment and collecting data at the Texas A&M University Riverside Campus. Later events pertain to intersection installations and data collection.

DATES AND ACTIVITIES

Oct 9, 2014

TTI contacted Trafficware to discuss project objectives and the number of sensors and components needed.

Oct 10

TTI contacted Twincrest Technologies to discuss the Wavetronix components to be purchased for this research project. We ordered one Wavetronix SmartSensor Advance (SS-200E) and one Wavetronix SmartSensor Matrix. Other components included the Click! 650.

Oct 20

TTI met with Texas Highway Products to receive Aldis equipment and be shown how to connect the equipment and its setup.

Oct 23

TTI met with three Iteris representatives to discuss setup of the Iteris Vantage Vector hybrid detectors.

Oct 27

The TTI research supervisor scheduled and held a phone conference with Twincrest and Wavetronix representatives from Utah to discuss project objectives and project support needs.

Nov 6

TTI took its Class 8 truck (Freightliner) to the selected runway at Riverside to determine its acceleration capabilities. Based on this activity, TTI selected the southbound direction due to greater acceleration length. The northbound direction would have accommodated speeds up to 50 mph but not 70 mph. Both the Wavetronix SmartSensor Advance and the FLIR TrafiRadar were advertised to detect trucks vs. non-trucks so both detectors allowed the user to set different dilemma zone ranges for trucks.

Nov 10

TTI moved a TS-2 cabinet from the Gibb Gilchrist building lab on the main campus of Texas A&M University to Riverside runway 35C and mounted it on a custom pedestal built by the project team.

Nov 11

TTI field personnel installed the two horizontal components of what would become a U-shaped mounting bracket to support some of the detectors that needed an overhead mount. On this date, TTI installed two Iteris Vantage Vector detectors on this support closest to the pole. The initial field data collection plan assumed that collecting data in both directions might be feasible, so TTI mounted one Vector facing north and the other facing south. An Iteris representative was on site for the installation. Iteris supplied the two detectors and two 500-ft spools of cable.

Nov 18

TTI team members met at Riverside to discuss strengthening the support for the sensors. At that point, the support consisted of only two horizontal aluminum members with threaded ends. Our discussion centered on adding a vertical member to connect the two horizontal ones by using a third connector, also with threaded ends. This addition would form the “U” noted above.

Nov 25

A representative from Twincrest Technologies was on site to install the Wavetronix SmartSensor Advance and SmartSensor Matrix. TTI installed the Advance on the top center of the U-shaped support and the Matrix at about 17 ft above the pavement fastened directly onto the pole.

Dec 4

TTI installed the Aldis system, including the fisheye camera and two upstream (called rectilinear) cameras. We placed them at the end of the support on the bottom level. The dome (fisheye) camera weighed about 10 pounds, and with the weight of it plus the other two cameras the support deflected downward. On the following day, TTI installed a diagonal cable to bring it back to level on the bottom.

Dec 10

TTI conducted a demo of installed systems for TxDOT visitors who were also visiting several other sites at Riverside and elsewhere. The group included the new RTI director.

Dec 16

TTI, guided by manufacturing reps, completed final modification to the Wavetronix and Aldis systems. The upstream Aldis camera facing south had slipped downward compared to the last time we were on site, so TTI personnel who installed the diagonal support cable might have bent the camera support. I was able to bend it back and set the camera as directed by Texas Highway Products reps on the ground. Initially, they encountered problems with the GridSmart computer not recognizing the third camera. After talking with their tech support, they found that a USB drive connected to the unit was the problem.

Twincrest installed software on a TTI laptop for both the Matrix and the Advance detectors.

Vehicles we ran at 50, 60, and 70 mph were: F-150 Ford pickup, a motorcycle, and the Freightliner. The big truck required almost the entire north end of the runway to accelerate to 70 mph.

TTI also installed a CCD camera to monitor the entire approach for ground truth recorded video. We connected it using a BNC to BNC adapter and taped with electrical tape since it was outdoors. The electrical connection is via a long extension cord, so both of these were temporary.

TTI left the white pavement tape and primer in the cabinet for adding to the pavement at the next opportunity. We talked about placing “tick marks” along the approach every 100 ft (or maybe less). This might help us in verifying vehicle distance. We placed the stop line (as indicated by cones) at about 42 ft from the pole (2 construction joints plus about 2 ft).

Dec 18

TTI continued tests of the Aldis, Wavetronix, Iteris, and FLIR (however their systems needed to be checked before considering this a final test). An Iteris rep checked adjustment of the two Vectors and was content with the initial results.

TTI connected to the FLIR TrafiRadar (hybrid that used video at stop line and Doppler radar for upstream detection) and IR camera with VIP card in the rack. We did not have the cable to connect to the TrafiRadar. The IR camera had shifted slightly so its detection zones needed to be shifted back into position.

Dec 22

TTI realigned the IR cam and checked the TrafiRadar to check distance from the stop line. It measured 42 ft from the pole. To assist in determining distances, TTI placed large white numbers along the southbound runway using pavement tape to indicate distances from the stop line on the "approach" at 400 ft (large "4") and at 800 ft (large "8"). On this date, TTI also installed an improved camera for monitoring vehicles on the approach.

Dec 23

TTI verified the distances to each "tick mark" along the runway using a measuring wheel first, followed by a more accurate tape measure. The data collection effort used these 100-ft tick marks for mounting the Trafficware magnetometers. Each pod was initially placed on top of the pavement with no adhesive, but without adhesive the pods occasionally shifted causing detection errors.

Also on Dec 23, TTI received shipment of the Trafficware equipment. The order included 9 pods, one Access Point and a Base Station. Trafficware technical support guided us using Skype to get the setup going in the lab.

TTI connected the TrafiRadar using the TTI laptop. The IR camera zones had shifted and needed to be adjusted so TTI contacted Control Technologies technical support to schedule a visit during the first week in January.

Jan 6, 2015

Two Trafficware representatives came to Riverside to install their system components. Initially, the Trafficware system had problems communicating with the Econolite ASC/3 controller. TTI brought the controller back to the office to troubleshoot the issues.

Jan 7

TTI researchers went to Riverside to try to resolve the Trafficware issue with the controller. We were able to get all 9 pods to communicate with the cabinet. Trafficware said the range should be around 700 ft, but we placed them as far away as 900 ft and successfully communicated with them although the signal strength was lower at greater distances.

TTI researchers developed a program to determine distances from a GPS unit in a vehicle on the runway to a second GPS unit at the cabinet. The GPS equipment was mounted in a TTI Toyota Highlander for most of the testing for this project. In early January, we tested the distance “measured” by GPS (again, one in the Highlander and one at the cabinet). Results indicated reasonably good accuracy using GPS to within a few feet. TTI continued to tweak the GPS hardware and software until the best results were being generated.

Jan 8

TTI technicians installed a more permanent antenna on top of cabinet. Due to problems with both FLIR systems (TrafiRadar and VIP with IR camera), Control Technologies came to help move the two systems to a lower point on the pole. TTI modified the aluminum (2-inch OD) pipe to improve the support stiffness for other detectors.

The research team met to discuss the needed sample size (number of vehicle passes through the detection zone) for each set of conditions.

Jan 13

TTI ran some trial runs to get a better idea of the safety and other aspects of running at the desired speeds of 50 mph and 70 mph. The initial runs used the TTI Freightliner (Class 8 truck-tractor) followed by the Toyota Highlander (equipped with Trimble GPS) at about 300 to 400 ft behind (not set) at a speed of 50 mph. The second set of runs was also at 50 mph then increased to 70 mph. The third set of runs used closer vehicle spacing (about 3 sec, although we planned 2 sec).

Jan 15

The research team began to feel more confident about the test site layout and the necessary data collection activities. Drivers made 10 runs at 50 mph and 10 runs at 70 mph with the Freightliner, the Highlander, and a TTI SUV.

Twincrest Technologies was on-site to monitor the Wavetronix Advance 200-E but did not change anything. The rep had set 2.5–5.5 sec for non-trucks and 2.5–7.5 sec for trucks. However, most of the vehicles were being detected at around 800 ft so the rep concluded that it was probably treating them as trucks. We discussed resetting to 2.5–5.5 sec for all vehicles but decided to leave them as-is for the time being.

At this point we had decided to only have one vehicle at a time in the detection zone due to earlier difficulties with data analysis. Minor problems with the GPS forced us to redo some runs.

The distance from the pole to the GPS mounted on the cabinet was 8 ft 7 inches from center of the pole to the cabinet mounted GPS. That makes the CORRECTION FACTOR for distance from stop bar to GPS at cabinet 42.5 ft minus say 8.5 ft = 34.0 ft.

Jan 15

TTI had to redo 20 GPS runs. We only used the Highlander but found that the range available from the GPS radios was over 2,000 ft. This was determined to be more than sufficient for this project.

Jan 21

TTI collected data 10 runs at 50, 60, 70 mph with four vehicles: the Freightliner, a full-size motorcycle, a Highlander, and an F-150 (#97). An Iteris representative was on site to monitor the Iteris Vantage Vector system facing north and checked speeds and distances as vehicles passed through. He did not indicate any problems. No known issues were obvious with other detectors.

Jan 22

TTI collected daytime rain data on this date. Rain fell the entire time, although after about the first 10 to 12 runs it was lighter rain. Problem with Trafficware pods: #2, #4, and #6 (at 200, 400, and 600 ft from stop line) at some point rotated about 20-30 degrees from parallel with traffic. The field person monitoring the cabinet found that a couple of the pods were stuck on (continued on after vehicle passed). TTI determined that adhesive should be used to keep the magnetometers in place to avoid movement or rotation. Three vehicles were being used: the Freightliner, an F-150 (#97), and the Highlander (GPS equipped).

Also, on Jan 22, local Iteris representatives sent an email message indicating that the radar detectors would interfere with each other if operated simultaneously due to their close proximity. TTI immediately called Twincrest Technologies to inquire about potential problems. This rep said that there would not be a problem with the SmartSensor Advance since it was on a different frequency than the Iteris or Traficon. However, the SmartSensor Matrix transmits at 24 gHz (same as the Iteris and Traficon) so there might be interference. TTI subsequently contacted a Wavetronix rep in Utah to see if he could offer suggestions as to how to determine whether the detectors were interfering with each other and if so how to keep them from interfering.

We followed that conversation with a three-way phone call between the TTI Research Supervisor, the Twincrest rep, and the Utah Wavetronix rep. The general outcome of the call was that the Utah rep did not know for sure whether the other two radar detectors might interfere with each other or with the Wavetronix, or vice versa. What he did say was that we would probably just have to operate them together and watch the output to see if any anomalies are obvious. He said the Advance would probably not be affected, but he could not say for sure. In summary, it became clear that there COULD be interference but there was no known way to know for sure. Therefore, to be on the safe side, the research team decided to run each radar detector separately. The exception was to run the Advance and Matrix simultaneously.

Jan 26

Representatives from the three radar detector manufacturers were on site to monitor their respective systems to look for indications that there might be interference with their respective radar systems due to other radar detectors operating simultaneously in close proximity. With just the Iteris Vantage Vector and the TrafiRadar running together there appeared to be no problems. However, with the Wavetronix Advance and Matrix running at the same time with both the Iteris and FLIR units running there seemed to be some minor problems. I thought the issue might be the Matrix since it operates at the same frequency as the other two so we turned it off for a few runs with two vehicles—Highlander and F-150. The Iteris rep said he saw one suspicious detection, not at the usual 600 ft but at something less (about 500 ft). He was not sure it was due to interference, but we agreed to do more data collection the following day.

A representative from Texas Highway Products was on site but did not see any problem with the Aldis system. However, the wind was not as high as it had been when false detections were occurring earlier. We decided to connect a third horizontal pipe midway between the two existing pipes on the overhead support to increase rigidity. He later provided another Astro-bracket, pipe, and some clamps for the outside end.

Jan 27

An Iteris representative was on site to determine possible interference from other radar detectors while the following vehicles passed: Freightliner, F-150, and Highlander. We used this dataset for the Interim Tech Memo due Jan 30, 2015.

Jan 29

TTI attempted to quantify the detection characteristics of the Trafficware pods by installing piezoelectric detectors at the stop line and at 400 ft and connecting them to a Jamar counter. The resolution of the counter was sufficient for this purpose (millisecond resolution) but its clock drift became an issue so TTI repeated this exercise later using tapeswitches connected to a laptop.

Feb 4

Texas Highway Products representatives were on-site for installation of the brace to strengthen the bottom support (at 32 ft). That afternoon, we conducted 10 runs for each radar detector (so 40 runs for everything that does not use radar). Vehicles were: F-150, F-150, Ford Fusion, (#96), and the Highlander.

Today was first day to use the Pelco DVR to record video data of vehicles passing the detection zone. We had installed a camera a few weeks earlier. The video should also show timestamp.

Feb 5

Discussed data collection procedure with the TTI statistician. The field team collected data: 30 runs at 70mph with four vehicles—Freightliner, F-250, Ford Fusion, and Highlander.

Feb 6: I contacted Control Technologies to tell them we were getting more than the expected 3.0 sec of dilemma zone protection with the TrafiRadar. He told me the TrafiRadar has the capability of setting different thresholds for cars vs trucks. When he set up the TrafiRadar at Riverside, he set 2.5 sec for cars and 7.5 sec for trucks. When I asked how the TrafiRadar classifies trucks from non-trucks, he said he did not have that information. Our tests should determine two things: 1) How well does it determine trucks from non-trucks, and 2) how much time does it provide for trucks (and non-trucks) once detected?

Feb 9

Vehicles used: F-250, F-150, and Highlander. We also had the Freightliner available but mechanical issues forced us to stop running it after one run. We followed that with only runs with the Highlander and two pickups.

Data collected at Riverside indicated that the Wavetronix Advance was holding the call for each vehicle for 5+ sec, so I contacted Twincrest to determine what to do. The result was setting 2.5 to 5.5 sec in the detector for all vehicles. **That means that previous data probably from the Advance should not be used or state why it was holding the call for 5+ sec.**

Feb 10

Night data collection. Four vehicles (no Freightliner due to mechanical problem) [ALDIS FISHEYE ONLY, NOT UPSTREAM].

We conducted three sets of 10 runs at 50 mph—one with two Wavetronix units turned on, one with TrafiRadar turned on, and one with the Iteris turned on. Therefore, we completed 30 runs for each of the non-radar sensors. The upstream Aldis detector was not working so we ran the tests without it.

Feb 11

TTI met with Texas Highway Products at Riverside to let them troubleshoot the Aldis detector since it was not recognizing vehicles at night with the upstream camera. After investigating, they concluded that it was still fully operational and ready to collect data. They suggested parking a car within the upstream detector zone after dark with lights on and let the detector adjust to it.

Night data collection. Four vehicles were used: F-150, Ford Explorer, Dodge Caravan, and Highlander. We intended to run 10 runs at 50 mph to finish the Aldis night data collection, but parking a vehicle in the detection zone did not help. TTI parked an F-150 in the zone with lights on then started data collection by conducting 30 runs at 70 mph. However, for the Aldis, only the fisheye camera was working. Again, we ran the radar detectors one at a time to ensure no interference.

Feb 11 Summary
Iteris On:

- 70 mph/night: F-150, Minivan, SUV, Highlander—10 runs

TrafiRadar on:

- 70 mph/night: F-150, Minivan, SUV, Highlander)—11 runs

Wavetronix on:

- 70 mph/night: F-150, Minivan, SUV, Highlander—12 runs

Feb 12

TTI collected more night data but started the Aldis before dark to see if it would recognize the upstream camera. It would not do it if started AFTER DARK the previous two nights. Results: the Aldis was able to start collecting data thru the upstream camera by starting it just before dark and letting it transition. We collected data at 50 mph and 70 mph. An incident caused the research team to stop using the Highlander and finish the data collection using another vehicle.

Source of Sunrise/sunset:
http://www.wunderground.com/history/airport/KCLL/2015/2/12/DailyHistory.html?req_city=College+Station&req_state=TX&req_statename=Texas&reqdb.zip=77845&reqdb.magic=1&reqdb.wmo=99999 accessed April 27, 2015.

Feb 12
Iteris On:

- 70 mph/dark: F-150, Ford Explorer, Minivan (#84)—15 runs

TrafiRadar on:

- 50 mph/dark: F-150, Ford Explorer, Highlander—15 runs.

Wavetronix Matrix and Advance on:

- 70 mph/dark: F-150, Ford Explorer, Highlander/#84—15 runs (incident with Highlander).

Feb 13

TTI staff met to discuss data analysis. Primarily, the discussions centered on development of two spreadsheets—one for the GPS data and the other for the detector data.

Feb 17

TTI collected detector data. This is the first day TTI used the Dodge Caravan (#84) for the GPS equipment (formerly used in the Highlander).

Feb 17
Iteris On:

- 50 mph/night: F-150, Ford Fusion, Caravan (#84)—15 runs

TrafiRadar on:

- 50 mph/transition: F-150, Ford Fusion, Caravan/#84—15 runs

Wavetronix on:

- 70 mph/night: F-150, Minivan, SUV, Highlander—12 runs.

(Second set of runs)
Iteris On:

- 70 mph/night: F-150, Ford Fusion, Minivan (#84)—10 runs

TrafiRadar on:

- 70 mph/night: F-150, Ford Fusion, Caravan/#84—10 runs

Wavetronix on:

- 70 mph/night: F-150, Ford Fusion, Caravan (#84)—10 runs.

Feb 18

TTI again installed piezo sensors to collect vehicle axle data while collecting the other data for the purpose of gaining a better understanding of the magnetometer detection characteristics. We started late pm during daylight and long shadows with TrafiRadar on and other radars off. From 5:45 on is considered dusk data (changing light condition).

Feb 18
Iteris On (4 vehicles):

- 50 mph/transition: F-150, Ford Fusion, MC, Caravan #84—11 runs x 4 vehicles

TrafiRadar on:

- 50 mph/transition: F-150, Ford Fusion, MC, Caravan/#84—12 runs x 4 vehicles

Wavetronix on:

- None.

(50 mph runs)
Iteris On (3 vehicles):

- 50 mph/night: F-150, Ford Fusion, Minivan (#84)—15 runs x 3 vehicles

TrafiRadar on:

- 50 mph/night: F-150, Ford Fusion, MC, Caravan/#84—10 runs x 4 vehicles

Wavetronix on:

- None.

Mar 2

TTI met FLIR representatives at Riverside, including a Traficon representative from Belgium who was in the United States for a short time. The Belgium engineer wanted to maximize his availability to tweak the TrafiRadar while he is in the United States. Below are some of the points shared by the Belgium engineer:

- The TrafiRadar classifies trucks based on length. TTI asked him to clarify because that did not seem like a good way to do it. He confirmed by adding that the default value was 10 m (about 30 ft), but the firmware did not seem to be as user definable as it should be.
- There is no handoff from the radar to the video as each vehicle approaches. The radar tags each vehicle, but the video does not look for that same vehicle.
- The TrafiRadar provides a warning within the user interface when interference from other signals occurs. It has to be in “streaming” mode I believe (as opposed to snapshot mode).

- The Traficon engineer tweaked the system, although I did not notice any major issues during previous data collection sessions.
- The hybrid can monitor as many as 32 or 64 vehicles on an approach at a time.
- The Traficon engineer said the detector could be raised slightly and achieve a longer detection starting point, say 600–650 ft instead of the current 550 ft.

Mar 4

TTI collected both dry and rain data in the afternoon. We started collecting data before the arrival of a strong cold front which brought rain with it. We conducted two sets of 10 runs each with four non-truck vehicles, first at 70 mph then 50 mph. The Freightliner became available just as the rain started at around 3:20pm. Vehicles during the early non-truck tests were: F-150 (#97,), F-150 (#43), Dodge Minivan (#84), and the Highlander. This was the first set of runs using the Highlander after the incident on Feb 12.

We found out when the Belgium engineer with FLIR/Traficon was here that the TrafiRadar outputs a warning if there is interference from a nearby radar unit. Therefore, we conducted tests on this date with TrafiRadar and Wavetronix running simultaneously and did not see any issues.

Data collection during the rain was ONLY at 50 mph (after about 3:15 p.m.). Vehicles used and their order: Freightliner, F-150 (#97), Dodge Minivan, and Highlander. We started with 25 runs with both the TrafiRadar and Wavetronix running followed by 15 runs with only the Iteris. We finished by 5:30pm at which time the rain had practically stopped.

DO NOT USE TRAFIRADAR DATA FROM THIS DATE (MAR 4) THRU MARCH 23

March 4
Iteris On (Dry, Day):

- None.

TrafiRadar on AND Wavetronix on:

- 70 mph/day, dry: F-150 (#97), F-150 (#43), Minivan, and Highlander; 10 runs.

Iteris on (Day, RAIN):

- 50 mph/day, rain: Freightliner (TRK), F-150, Minivan, Highlander—15 runs

TrafiRadar on AND Wavetronix on (RAIN):

- 50 mph/day, rain: TRK, F-150, Minivan, Highlander—25 runs

Wavetronix on:

- None.

Mar 17

Two TTI research engineers went to Houston to meet with Houston District field personnel to collect data at the FM 2920/Hannover Woods intersection. TTI used one of the cameras already installed at the intersection to count vehicles at the stop line as a prelude to full-scale tests.

Mar 23 (Back to Riverside)

Weather: day, dry (partly cloudy). Based on earlier data sent by local reps from Control Technologies to Belgium, the Traficon home office phone recommended tilting the TrafiRadar up to give it more range. Headquarters told Control Technologies that it should reach out further than it currently did. Also, Iteris reset the Vantage Vector to take it off “continuous” mode following a lawsuit alleging that Iteris infringed upon the Wavetronix patent regarding continuous detection using Doppler radar. The settlement forced Iteris to stop using the continuous mode for new detectors. At that point, TTI expected FLIR to be sued next since they had not been sued even though the TrafiRadar also used a continuous mode for its Doppler radar detector which appeared to be similar to Wavetronix’ continuous mode. At about this same time, we found out that Traficon was also working on a “fix” that would be similar to the Iteris fix to replace the continuous mode with a trip line mode.

An Iteris rep reset the Vantage Vectors to collect trip line data instead of continuous data even though Iteris could only use one or two trip lines as an interim feature. The Iteris permanent fix for replacing their continuous mode would not be available until the end of summer 2015. TTI was told that the permanent fix would offer more flexibility in the use of trip lines and more than two trip lines.

Also March 23, TTI collected data for 12 runs to make sure the Iteris Vantage Vector was working at 50 mph. The on-site rep set two detection zones for the desired speeds being used (50 mph and 70 mph). He later provided the following distances:

- Trip 2 - 566' - 65 mph - 3 sec extension so anything above that speed (e.g., 70mph) SHOULD send a 3-sec extension to the controller; vehicles traveling below that speed should not result in extension.
- Trip 1 - 485' - 45 mph – 3-sec extension so anything above that speed (e.g., 50mph) should send a 3-sec extension to the controller; below that speed should not send an extension.

DO NOT USE ANY ITERIS DATA PRIOR TO MAR 23 DUE TO LAWSUIT

Mar 30

Weather: day (mostly clear), dry. Vehicles in order: Freightliner, F-150, Ford Fusion, then Highlander. Based on input from the same Belgium engineer as before, TTI adjusted the TrafiRadar upward but it would not detect the Highlander in that orientation. Therefore, a Control Technologies technician (who was on the ground guiding the change) recommended tilting it back downward and panning it about 10 degrees left. This downward tilt adjustment was contrary to what the Belgium HQ engineer had recommended. Earlier, it detected the Freightliner and the pickup but not the Highlander. It apparently was aimed too high and was detecting the top of the Highlander some of the time but missing it some of the time.

We conducted 25 runs at 50mph with the TrafiRadar turned on and the other two radars turned off. Then we collected about 21 runs with the Iteris, also at 50 mph. Measurement of the

Freightliner length (28 ft 10 inches) indicated that it would not quite meet the threshold for FLIR TrafiRadar to make it a "truck."

FOR FUTURE DATA USE:

Iteris Vantage Vector: Do not use any data prior to March 23 due to lawsuit.

TrafiRadar: Do not use data from March 4 thru April 1 due to faulty settings and updated firmware being worse than original firmware. Control Technologies called TTI on April 6 and asked us not to use the data collected using the revised firmware from Headquarters and allow Jon to reinstall the old firmware. TTI agreed to comply with the request but cautioned that any additional changes would jeopardize continued testing of the TrafiRadar.

March 30
Iteris On:

- 50 mph/day: TRK, F-150 pickup, Ford Fusion, Highlander—21 runs.

TrafiRadar on:

- 50 mph/day: TRK, F-150, Ford Fusion, Highlander—25 runs.

Wavetronix on:

- None.

Apr 1

Given that the Freightliner was not quite 30 ft long and TTI needed to include a vehicle of at least that length to test the truck/non-truck determination by the TrafiRadar, the decision was made to use a pickup pulling a trailer to achieve the 30-ft length. Vehicles used on this date: F-150 pulling 18-ft flatbed 2 axle trailer (total length pickup plus trailer was 42 ft), Ford Fusion (#98), and TTI Highlander. We completed 20 runs at 70 mph for FLIR TrafiRadar, then 20 runs at 50 mph for TrafiRadar, then 10 runs with Iteris at 70 mph. This is the first time we used the pickup with trailer to test TrafiRadar detection of trucks vs. non-trucks. The weather forecast had over 50 percent chance of rain, but there was NO RAIN at all. It was overcast all afternoon. We started around 2:00 p.m. and ended around 4:30 p.m.

Apr 2

TTI planned on collecting data during transition and possibly night. However, given the problems TTI was encountering with the detectors (e.g., lawsuit between Wavetronix and Iteris and multiple changes to the FLIR TrafiRadar), there was an urgent need to get input from the project monitoring committee regarding how to complete the project. TTI contacted RTI to request that a meeting be scheduled with the committee to discuss the options.

Apr 3 (Good Friday)

I left another message for RTI requesting that a meeting be scheduled with the PMC (next week). I was out of the office that afternoon, but no messages came from RTI during that period.

April 1 (Day, Dry)
Iteris On:

- 70 mph/day: TRK, F-150 pickup, Ford Fusion, Highlander—21 runs.

TrafiRadar on:

- 70 mph/day. TRK, F-150 pickup, Ford Fusion, Highlander—25 runs.

Wavetronix on:

- None.

Since we reset the Wavetronix Advance to monitor only non-trucks before this date and we removed the TrafiRadar from further tests, there was no longer a need to test using a long vehicle.

Following week: RTI scheduled a meeting with the PMC to discuss alternatives. After discussing the options, the panel recommended discontinuing the TrafiRadar but to continue testing the other selected detectors. An RTI spokesman indicated that the additional funds needed to complete the project would have to come from FY 2015 funds since FY 2016 funds were already fully committed. TTI explained that the project would benefit significantly from additional time but would do its best to complete the work within FY 2015 if given no other option. The result was additional funding added but no additional time.

Apr 6 **(NEITHER FLIR TrafiRadar nor Iteris were working well on this day)**

Control Technologies called to discuss the performance of the TrafiRadar. According to the spokesman, new firmware was not performing as well as the old firmware. The Belgium engineer had replaced the firmware a couple of weeks earlier, and that caused the decline in performance. We agreed not to use the data using the new firmware since we had considerable data using the old firmware anyway. Control Technologies sent a technician to Riverside on this date to replace the firmware.

The Control Technologies technician arrived at Riverside around 2:15 p.m. to replace the new firmware in the TrafiRadar with the original firmware. TTI reoriented the detector based on the technician's guidance from the ground. TTI panned the detector to where it was before (10 degrees right) and also centered the bubble on top (although it was within the circle already). TTI drove through the zone about 10–12 times while the technician watched and tweaked the detector until about 4:30 p.m. At the end of it all he was frustrated and was not happy about the result. He mentioned that the radar and video alignment were not consistent. TTI believes this is a major flaw in the design of this detector—having both detectors in the same enclosure with only one adjustment on orientation. The Iteris hybrid, on the other hand, allows individual adjustment of video and radar.

Apr 6 (same date)

Vehicles used: F-150 (# 97), Ford hybrid (#82), and Highlander. We collected light transition and dark data, starting at 7:00 p.m. and finishing at about 8:30 p.m. Sundown on this date was

7:47 p.m. according to Wunderground. We collected data at 70 mph (10 runs) followed by 50 mph (also 10 runs) with the Iteris Vantage vector on and other radars off. Then we turned on the TrafiRadar for 10 runs as darkness approached (other radars off). We finished with the TrafiRadar at around 8:10 p.m. Regarding the Iteris data collection, we noted that the Vector failed to detect 10 of the 30 vehicle passes at 70 mph (i.e., missed them at both trip lines).

TTI called the Iteris rep and he came to Riverside the following afternoon after 5:00 p.m. The Iteris rep asked whether all other radars were off so we made sure they were, plus we would have noticed detections in the output if others had been turned on.

April 6 (Night, Dry)
Iteris On:

- 70 mph/transition: F-150 (# 97), Ford hybrid (#82), and Highlander.—10 runs x 3 vehicles
- 50 mph/transition: F-150 (# 97), Ford hybrid (#82) and Highlander—10 runs x 3 vehicles

TrafiRadar on:

- None.

Wavetronix on:

- None.

Apr 8

The Iteris rep was on site to check his system to see if what we saw on April 6 would be repeated. He monitored the system from the cabinet as we drove the following vehicles through the detection zone: F-150 (#97), F-150 (#43), and Toyota Highlander.

- File 1: 11 runs at 70 mph and extension of 3.0 sec in the Vantage vector; it missed #97 (F-150) three times. We do not know of any explanation for it missing this F-150 and not the other one (although their shape is a little different). Its performance was much better at 50 mph, but we only did a few runs at that speed.
- File 2: Reduced extension time to 2.5 sec for both trip lines.
    - Run 1 at 50 mph (3 vehicles).
    - Run 2 at 70 mph (same 3 vehicles) and resulting extension (based on our procedure) was around 3.0 sec. When set at 3.0 sec in the detector, our data showed more than 3.0 sec. We did two cycles of 50 mph then 70 mph. For those four runs we evaluated the extension time.
    - Channel 14: near tripline at 485 ft.
    - Channel 15: far tripline at 566 ft.
- File 3:
    - Run 1: extension 2.5 sec (only 2 runs, 3 veh).
        - 50 mph.
        - 70 mph.

  - Run 2: extension 3.0 sec (only 2 runs, 3 veh).
    - 50 mph.
    - 70 mph.
  - Channel 14: near tripline at 485 ft.
  - Channel 15: far tripline at 566 ft.

Apr 9

The solution to the Iteris Vantage Vector involved raising the radar detector to increase its range. The Iteris rep came to the runway around 3:00 p.m. TTI brought the Eagle Lift out and changed the orientation of the Iteris radar, tilting it up about 5-10 degrees. We ran 10 runs at 70 mph with three vehicles: F-250 (#83), F-150 (#43), and Highlander. Performance of the detector seems to have improved. It completely missed one vehicle with both trip lines and saw two other errors in the 30 passes. Earlier in the week (April 6), it missed 10 out of 30 passes.

The other finding from talking to an Iteris engineer prior to this date was that the resulting extension includes a "presence" time within the trip line area. Therefore, if the user inputs 3.0 sec into the extension for each detector, the resulting signal output by the detector exceeds the 3.0 sec by some amount. Our findings indicated that this additional amount is less at higher speeds, which is consistent with the presence concept. In other words, the faster a given vehicle travels the less time it will occupy a fixed space.

April 9 (Day, Dry)
Iteris On:

- 70 mph/day: F-250 (#83), F-150 (#43), and Highlander—10 runs x 3 vehicles

TrafiRadar on:

- None.

Wavetronix on:

- None.

Apr 16 **DO NOT USE FLIR RADAR DATA**

This test was primarily for the FLIR TrafiRadar. Two Control Technologies reps were on site to improve its performance. We met at Riverside at about 10:00 a.m. to get started. TTI provided the Eagle lift to reorient the TrafiRadar and to remove the south-facing Aldis camera. Control Technologies first asked TTI to raise the radar aim upward to increase the detection distance on the approach (since video aim is the same, it also raised the stop bar detector). TTI drove vehicles through the detection zones a few times, but the Control Technologies reps did not like the results. Right after lunch, one technician asked TTI to reorient the detector to bring the radar beam back down slightly. TTI measured the tilt on the radar face using an iPhone app and found that it was −1.3 degrees. The bubble on top of the unit was apparently intended to a 0-degree orientation, so the bubble was not centered. This all indicates that the unit has an undesirable design since the installer cannot adjust the radar and video detectors independently.

An Iteris rep was also on site to collect data, but at the end of the TrafiRadar runs the rain started accompanied by lightning/thunder so we decided not to collect more data. The rain barely allowed completing the TrafiRadar data collection (6 runs, 4 vehicles at each speed). We needed rain data as well, but lightning made conditions unsafe. The Iteris rep commented that TxDOT's Traffic Operations Division wanted Iteris to implement three trip lines instead of only two. Of course, that would have involved a major firmware change by Iteris and was beyond our control.

April 16 (Day, Dry)
Iteris On:

- None

TrafiRadar on:

- 70 mph/day: F-150 (#68), Caravan, unspecified vehicle 3, and Highlander—6 runs × 4 vehicles

Wavetronix on:

- None.

April 16

Removed Aldis camera pointed south so turned off power to entire detector and left it off.

Week of April 20

TTI removed the Aldis switch from the Riverside cabinet. We would need to reconnect the remaining rectilinear camera but will not need the switch for that.

Apr 29

Vehicles used: F-150, Caravan, and Highlander. Day/transition: started around 5:00 p.m. and stopped at 8:30 p.m.

April 29 (Day, Dry)
Iteris On:

- 50 mph/transition: F-150, Caravan, Highlander—10 runs × 3 vehicles
- 70 mph/transition: F-150, Caravan, Highlander—11 runs × 3 vehicles

TrafiRadar on:

- None.

Wavetronix on:

- None.

May 5

Contacted Control Technologies to inform them that we would have to drop the TrafiRadar from further tests. TTI explained that the reasons for discontinuing its testing was that it had not performed well, and we were too far along on the project to wait on further enhancements from Belgium. When asked about a possible lawsuit (like Iteris), the spokesman commented that Traficon had developed a tripline option so the company is not concerned about a lawsuit.

Vehicles available for May 5:

- F-150 (#68).
- Dodge Caravan (#84).
- Toyota Highlander (#71).

TTI planned to collect rain data, but rain was too scattered.

May 6

TTI intended to collect rain data, but the rain stopped by the time researchers were ready to start collecting data (around 9:30 a.m.). We measured the "magnetic" signature of the Dodge minivan (#84) using Valence Pod #9 (at stop line) and did some presence time tests at 20, 40, and 60 mph. The 20 mph test was run twice, then 40 once and 60 once with the Highlander. TTI also recorded the van's passage on video. but the footage was not useful for determining presence time within the detection area.

May 11

Vehicles used: F-150 (#97), F-250 (Environmental) and Highlander drove to collect data while raining. Headlights were off for all vehicle runs. TTI began collecting vehicle data at 11:15 a.m., making 10 runs with 3 vehicles at 50 mph followed by 10 runs with 3 vehicles at 70 mph. Weather: Light to moderate rain the entire time with local thunderstorms.

TTI experienced some power issues at the cabinet that had to be remedied. We actually did not solve the problem but got an extension cord to power the other detectors. The problem seemed to be associated with the rain.

For radar detectors, we only tested the Wavetronix Advance and the Matrix. For non-radars, at first the Aldis seemed to be unstable but it settled down. We checked and turned on the FLIR IR camera with VIP. The IR/VIP will likely be compared against the Aldis system since it is video but not IR.

May 11, 2015 (Light rain)
Iteris On:

- None.

TrafiRadar on:

- None.

Wavetronix on:

- 50 mph/rain; F-150 (#97), F-250 (Environmental) and Highlander—10 runs with 3 vehicles.
- 70 mph/rain: F-150 (#97), F-250 (Environmental) and Highlander—10 runs with 3 vehicles.

May 15

Vehicles driven were: F-150 (#97), F-150 (#109), and Highlander. During the first run at 50 mph the Highlander headlights were on and also on the new F-150 but were turned off after run 1. This would only make a difference (if any) for video systems.

TTI started by turning off both Wavetronix detectors (had been turned on during the last data collection session). Light rain was falling the entire time for the Iteris but not as heavy as on Monday when we had the Wavetronix detectors running. We started around 3:30 p.m. and stopped at about 4:30 p.m. We collected data with the Iteris Vantage Vector on since we had not had a chance to collect rain data since Iteris stopped using the continuous mode. We did 14 runs (3 vehicles) at 50 mph then 13 runs at 70 mph. Some of the channels were showing a constant call at least while we were running 70 mph.

May 15, 2015 (Light rain)
Iteris On:

- 50 mph/rain; F-150 (#97), F-150 (#109), and Highlander.—10 runs with 3 vehicles.
- 70 mph/rain: F-150 (#97), F-150 (#109), and Highlander.—10 runs with 3 vehicles.

TrafiRadar on:

- None.

Wavetronix on:

- None.

May 28

TTI talked to Texas Highway Products to find out whether we should actually pursue data collection in Houston with the upstream cameras. We still plan on data collection with the fisheye camera but results from the upstream cameras were sporadic. The rep said he will contact the Aldis headquarters in Knoxville, Tennessee, to see what the upstream cameras are actually doing. If they do not provide a hold on the phase or something, it is not worth our time testing them.

Jun 2

Data collection began around 4:30 p.m. with the following vehicles: F-250 (#83), Motorcycle, and Highlander. We only had the Wavetronix radar detectors on, so no Iteris radar (no TrafiRadar since removed from further consideration).We only did 50 mph runs, none at 70 mph.

We conducted 25 runs with the Wavetronix on and Iteris off. The primary purpose was to get more motorcycle data, but we included the other two vehicles since they were available.

June 2, 2015 (Day)
Iteris On:

- None.

TrafiRadar on:

- None.

Wavetronix on:

- 50 mph/day; F-150 (#83), motorcycle, and Highlander—30 runs with 3 vehicles.

Jun 26

The following vehicles were involved in 25 runs at 50 mph (in this order): F-150 (#109), motorcycle, and Highlander.

We were short on motorcycle data for the Iteris Vantage Vector, so we turned off the Wavetronix units for this set of runs. Other systems that were still available were: Aldis, FLIR IR camera, and Trafficware pods.

A rep from Control Technologies met TTI at Riverside at 1:00 p.m. to remove the FLIR equipment. TTI used its Eagle lift to remove the TrafiRadar and the IR camera from the pole.

TTI also removed the Wavetronix Advance Extended Range and the Wavetronix Matrix since the Advance will probably need to be installed at an intersection soon. TTI still needs to go back to the cabinet and retrieve the Wavetronix components from there and disconnect the cable from the cabinet.

June 26, 2015 (Day)
Iteris On:

- 50 mph/day; DM (#109, new F-150); Sam (MC); DanW (Highlander)—30 runs with 3 vehicles.

TrafiRadar on:

- None.

Wavetronix on:

- None.

Also June 16, TTI met TxDOT at FM 973/FM969 to collect data with Trafficware sensors.

Jul 14

TTI planned to collect data on this date using tapeswitches to characterize the detection patterns of the Trafficware pods. The researchers developing a program using LabView were not far enough along with the program to collect the data on this date and predicted another full day to complete it. The software was intended to read a voltage increase from the tapeswitches with each wheel hit and generate a timestamp for each axle.

Jul 16

This was the first of two days of data collection using tapeswitches to define magnetometer ons and offs using the same space on the runway as used for detector data collection. In the cabinet only the Trafficware equipment was being monitored. We placed three magnetometers at 30 ft spacing with tapeswitches 1 ft past each Pod. Pod #1 was the first encountered by each vehicle, followed by #2 and then #3. Pod #3 was placed flush with the pavement nearest the cabinet but the other two were placed on the pavement surface.

Vehicles used on this date:

- F-150 (#109), (lead vehicle).
- Dodge Minivan (#84).
- Toyota Highlander (#71).

TTI conducted three sets of runs as follows:

- 10 runs at 30 mph.
- 10 runs at 50 mph.
- 10 runs at 70 mph.

Vehicle spacing was tighter than we had used for other detector tests before since the program would have been too large if we ran it continuously. This required a person to be at the laptop and hit “Start” as first vehicle passed and “Stop” as last vehicle passed. Vehicle spacing varied but was usually no less than 200 ft and no more than 400 ft.

Jul 17

This was the second day of data collection with tapeswitches and magnetometers. We left the tapeswitches down overnight but replaced the magnetometers. Pods were in the same order as the previous day and placed in the same positions.

Vehicles used on this date:

- Freightliner (lead vehicle).
- F-250 (Environmental).
- Ford Fusion (#96).

TTI conducted two sets of runs (due to limited time):

- 10 runs at 50 mph.
- 10 runs at 70 mph.

Jul 24

Two TTI engineers traveled to Austin to meet TxDOT to install a Vantage Vector and Wavetronix Advance SS-200E at RM 1431/Mayfield Ranch Blvd. Two Iteris reps were on-site to set up the detector. TxDOT mounted it on the back side of the intersection facing west. The Wavetronix was installed on the opposite mast arm also facing west but almost directly over the stop line. This site has a crest vertical curve, and the detectors are near the apex of the vertical tangents.

A Twincrest rep was on the phone from California to assist with the installation of the Wavetronix Advance (SS-200E). We had TeamViewer installed on the field laptop so he could log in and view the detections remotely. At the end of about an hour, he was not completely satisfied with the results, so we decided to control that approach with the Iteris Vantage Vector until Twincrest could visit the site. Apparently Iteris reps wanted to control both the thru and left-turn lane initially because they turned off the Matrix which was there for stop line detection. In other words, the Iteris was monitoring both phase 2 and phase 5.

The controller installed at the intersection was an Econolite ASC/3. There are two cameras that are not being used that could be reoriented and used to record video if needed. The installed Vector is using one of the coaxial cables that had connected the camera on that approach.

We left the intersection with the Iteris Vantage Vector controlling phases 2 and 5 (Matrix was turned off completely, I believe, in case it might interfere with the Vector operation).

Jul 27

TTI tried to contact TxDOT's Austin District to check on having a bucket truck available on Friday, July 31, to remove the two installed detectors. TTI had to leave a message as there was no answer. TTI also asked Twincrest to coordinate with TxDOT to set a time to meet at the RM 1431 intersection the following day (Tuesday). The Twincrest rep promised to do so, indicating that he was tentatively planning on being there around 10:00 a.m. Tuesday morning. I mentioned to the Twincrest rep that there was no bucket truck scheduled at this point, but the rep said that should not be a problem, thinking that the district could probably provide one on fairly short notice.

Jul 28

A Twincrest rep met TxDOT at RM 1431/Mayfield Ranch to check on the Wavetronix detectors installed there. We had installed the SS-200E on July 24, but the Twincrest rep was in California and only able to check the system remotely. Twincrest was able to connect remotely using TeamViewer on July 24, but there was some uncertainty as to the Advance SS-200E performance. Therefore we agreed not to collect official data until the Twincrest rep was able to return from another activity). We abandoned that approach and began working with the eastbound approach. That approach had a crest vertical curve upstream with slight downgrade approaching to visit the site. No TTI personnel were available to be there but TxDOT had someone available to meet Twincrest.

Twincrest and TxDOT left the Wavetronix Advance and Matrix controlling the eastbound approach to the intersection (phase 2 and 5), so we have data starting on that Tuesday.

In the meantime, we were able to check data from the Iteris Vantage Vector and found some suspicious results. Its shortest extensions were 1400 milliseconds, which was shorter than the 1800 m-secs set in the detectors (there was an additional 2.0 sec in the controller according to district policy). By Thursday of that week, Iteris called TTI to say that the detector was set up improperly, requiring additional data collection for the project. TTI then contacted TxDOT to schedule someone from Iteris and TxDOT to meet at the site and reset the detector.

Jul 29

A TTI engineer went to Houston to meet Control Technologies (FLIR), Twincrest, and TxDOT to install the FLIR VIP system with an infrared camera at FM 1488/Kuykendall. TxDOT had two bucket trucks available at 9:00 a.m. to start the work. The controller was a Siemens EPAC 300, but it did not have an Ethernet port so TTI requested a different controller equipped with Ethernet capability. TxDOT agreed to do that, but they would not be able to bring one out until at least the following day.

This intersection (and others nearby) are in coordination mode weekdays from 5:45 a.m. to midnight 12:00 a.m. and on weekends from 8:00 a.m. to midnight 12:00 a.m.

The initial plan was to install both of the test systems (SS Advance and IR camera) facing east to capture westbound traffic because that direction had the longest view of approaching traffic. Detectors already installed included dome cameras (initially thought to belong to the county but later we were told they had been turned over to TxDOT), standard cameras, and Wavetronix Advance, and Matrix. The plan was to install the IR camera from FLIR on an existing riser facing east, but when TxDOT removed that camera they discovered that the cable had been cut (probably used as a pull cable the signal).

We worked until about noon with bucket trucks on-site, but with the issues needing to be resolved we decided to come back another day to finish. TxDOT will bring a different controller and Control Technologies would still need to set up the FLIR VIP system in the cabinet. Twincrest finished checking the Wavetronix systems and seemed to be satisfied with their operation. Besides, he had to leave at noon to go to another site.

Jul 30

Today’s activities mostly involved coordination of the Austin and Houston meetings between TxDOT and vendors. TTI was planning to go to Houston on Friday.

Iteris called me either Wednesday or Thursday to say that the detector was set up improperly. Each of the three upstream detectors would require separate channels instead of the three connected to the same channel. Using the additional channels required that the Matrix control phase 5 instead of having the Iteris do it. I then contacted TxDOT to schedule someone from Iteris and TxDOT to reset the detector.

Jul 31

TTI returned to the intersection of FM 1488/Kuykendall to meet TxDOT and Control Technologies to finish the installation of the FLIR equipment and begin collecting data with a laptop connected to the controller. TTI had problems in the laptop setup but at the last minute decided to erase some files from the laptop to create space and it started working. We will be able to store actuations from the IR camera but need to use its output to record video.

An Iteris rep met TxDOT at the RM 1431/Mayfield Ranch intersection to reset the Iteris Vantage Vector. We will use the Wavetronix Advance SS-200E to record ground truth.

Aug 3

TTI used TeamViewer to see if the Wavetronix Advance had been left on (even though the Iteris was still controlling the eastbound through approach). TTI found that it was still running so we used its output to verify the Iteris.

Aug 5

One TTI engineer went to Austin to install a DVR to start recording video and change detection on the eastbound approach to Wavetronix Advance SS-200E. The Matrix was already controlling the left-turn phase (phase 5) on that approach because the Iteris Vantage Vector used the remaining three channels for its three upstream triplines. The DVR will only run about two days before requiring SD card replacement. The DVR is very small but has limited data storage space.

The only camera that was available facing west was the Iteris Vector camera. We were unable to receive an image from the camera on the west side of the intersection facing west and mounted on a riser. It would have been better than the Iteris camera because of its height and mounting location (Iteris was mounted directly on the mast arm on the east side).

On Monday, August 3, we heard from Iteris that they had a bug in their program pertaining to the first trip line. TTI talked to the Iteris rep and informed him that our data did not indicate a problem. The issue was that the first trip line would not generate an extension of more than 600 milliseconds (it was set to extend 1800 milliseconds). We are seeing extensions greater than that value indicating that there is 1800 milliseconds plus a presence time so we plan to use the data that we have collected.

Aug 7

TTI returned to RM 1431 to retrieve the SD card from the DVR at about 2:30 p.m. and replace it with a 64 gb memory card. TxDOT was supposed to meet him there although this was a busy day for them and someone besides the usual person might be assigned to meet him. This SD card should be sufficient for about four more days of video data collection. We had to reschedule the removal originally planned for Tuesday, August 11, because both TTI personnel were unavailable.

APPENDIX B. TRAFFICWARE POD PERFORMANCE CHARACTERIZATION

INTRODUCTION

Since the Trafficware magnetometers were new and relatively unknown to the research community, this research project needed to characterize the detectors' activation and deactivation performance. TTI conducted this experiment at the Riverside campus using the same vehicles as used for detector tests. The purpose of this experiment was twofold: 1) determine the characteristics of the Trafficware Pods, and 2) verify the position of vehicles as determined by GPS.

The overall objective of this project is to determine how the various detectors are actually functioning and to compare their actual operation to their intended operation as described in their documentation (manuals, specifications, etc.). The test runs involved running vehicles of different types along a section of Riverside runway replicating an intersection approach, recording the on and off times for all the detectors. Trafficware Pods (magnetometers) helped the research team track where vehicles were actually located during the test runs since they function as simple presence detectors.

Researchers used the valence pod observations to construct speed and position profiles for each vehicle test run. In other words, the research will determine the vehicles' speed, position, and time to stop line every time any detector is turned on or off. To construct these profiles, it is necessary to interpolate if the detector observation in question occurs between two valence pod observations, or extrapolate if it occurs after the last downstream valence pod is passed (i.e., observations downstream of the stop line).

For the valence pod observations themselves, the vehicle's position in space and time is known within the variability of the devices' operation. Some sources of variability may include:

- Uncertainty in the relationship between vehicle position (directly over the pod, just upstream of the pod, just downstream of the pod) and the pod's operation.
- Delay in the transmission of the pod's data back to the controller.
- Delay in the recording of the controller data to the logging program.

Of these three sources of variability, the first is likely the most important. Failure to account for Pod operation can result in consistent bias in the development of vehicle position and speed profiles. The second two variability sources, delays in transmission and recording times, will introduce some uncertainty into the position and speed profiles, but they represent inherent limits in the data collection system that was used, and cannot be corrected without redoing the test runs with a more sophisticated system.

Researchers believed, but needed to prove, that the Pods could function as ground truth locators of the vehicles during test runs. To obtain this proof, the research team needed to know how much variability existed within the on and off observations of the Pods. Questions that needed to be addressed were as follows:

1. Where is the vehicle located when the Pods actuate (turn on)? Is the vehicle's front bumper directly over the Pod, or a certain distance upstream of the Pod?

2. Where is the vehicle located when the Pods de-actuate (turn off)? Has the vehicle's rear bumper just departed from above the Pod, or is it a certain distance downstream of the Pod?
3. Are these trends affected by vehicle type?
4. Are these trends affected by speed?
5. Do all Pods behave in the same manner?

The answers to these questions may yield correction factors that could be applied in the interpolations and extrapolations that are used to compute vehicle position and speed profiles. These correction factors may include the following:

- "Lead" time, defined as the time elapsed between 1) detector actuation and 2) actual vehicle presence over the detector.
- "Lag" time, defined as the time elapsed between 1) vehicle departure from the space over the detector and 2) detector de-actuation.

The research team initially attempted to conduct this experiment using piezoelectric sensors on selected days (including January 29 and February 18) to obtain a validation dataset. However, connecting the two Class II piezo sensors to an available Jamar counter was unsuccessful in achieving sufficiently accurate data, primarily due to clock drift in the counter. Therefore, the search for an improved set of equipment and methodologies yielded an option using tapeswitches. This option would allow the axle sensors to communicate directly with the laptop PC in the field, therefore solving the clock drift issue.

METHODOLOGY

The research team spent two days collecting tapeswitch data at Riverside to define magnetometer ons and offs (activations and deactivations). The Trafficware system was the only one being monitored in the cabinet. The tests used three magnetometers spaced 30 ft apart along with tapeswitches positioned 1 ft past each Pod. Pod #1 was the first encountered by each vehicle, followed by Pod #2 and then Pod #3. Pod #3 was placed in a core drilled for Sensys Networks magnetometers about 2 years earlier while other Pods were placed on the pavement surface.

Figure 54 shows two of the three Pods in relation to the tapeswitches prior to these test runs. These two magnetometer were placed on the pavement surface and positioned 1.0 ft past the center of the two tapeswitches. A third magnetometer (not shown) was 30.0 ft downstream of the near magnetometer in this photo but placed in a 4-inch diameter hole drilled for this purpose. Testing did not indicate any difference in detection properties due to being mounted on the surface versus being mounted flush with the surface.

The TTI research team developed software using LabView to read axle hits with the tapeswitches and store them on a field laptop computer beside the runway at Riverside. Each vehicle passage triggered either two or three hits as each axle passed over the tapeswitches. Passenger cars and pickups caused two detections and the Class 8 truck-tractor caused three detections. The front and rear vehicle overhangs were important measurements in associating the wheel hits with the actual front and rear of each vehicle. Table 48 summarizes the pertinent vehicle dimensions for this experiment.

Figure 54. Photo of Magnetometers and Tapeswitches as Tested at Riverside.

Table 48. Pertinent Vehicle Dimensions for Characterizing Pod Performance.

Vehicle	WB (in)	Overall L	OH Front	OH Rear
2006 Toyota Highlander	107	186	39	40
Ford F-150 4×2 crew cab	145	231.9	37.8	49.1
Ford F-250 4×4	172.66	263	37.9	52.44
2009 Ford Explorer	113.7	193.4		
2011 Ford Fusion	107	101.7		
Freightliner Columbia (w/sleeper)	258	305	25.5	22.5

Note: All dimensions are in inches.

Vehicles used on the first day were as follows:

- Ford F-150 (1/2 ton pickup).
- Dodge Minivan.
- Toyota Highlander.

On the second day, Pods were in the same order as the previous day, but speeds were 50 mph and 70 mph. Vehicles used on this date:

- Freightliner Class 8 truck tractor.
- Ford F-250 (four-wheel drive pickup).
- Ford Fusion (sedan).

The outcome of the tapeswitch data collection effort was helpful in two ways: 1) determining the activation/deactivation characteristics of the Trafficware Pods, and 2) verifying the locations of vehicles approaching the intersection stop line. All speeds at Riverside was constant so vehicle location could be verified not only every 100 ft at Pod locations but at intermediate points as well through interpolation.

RESULTS

The following results consider each vehicle type and develop tabular and graphical depictions of the Pod detection characteristics. The on statistics are deemed the most important since some of the test detectors detect the front of the vehicle. The off statistics from the Pods were compared with actual passage of the vehicle's rear bumper using the known vehicle length. Table 49 through Table 54 summarize these findings along with Figure 55 through Figure 67.

For each of the six vehicles, the following results indicate first a tabular summary of descriptive statistics for the front of each vehicle, followed by a graphic plot of time latency versus speed (mph), and finally a trace plotted as distances showing pictorially the mean values of ons and offs. These results for specific vehicles are followed by an interpretation of findings for all vehicles.

Ford F-150 (1/2 Ton Pickup)

Table 49. Detector On Delay Stats for F-150 Ford Pickup.

	n	Mean	Variance	Std. dev.	Std. err.	Median	Range	Min	Max
All Speeds	90	17.81	61.95	7.87	0.83	17.19	33.65	7.25	40.90
30 mph	30	9.31	1.66	1.29	0.23	9.33	5.55	7.25	12.81
50 mph	30	17.95	11.48	3.39	0.62	18.13	13.86	11.40	25.26
70 mph	30	26.16	30.16	5.49	1.00	27.13	25.26	15.64	40.90

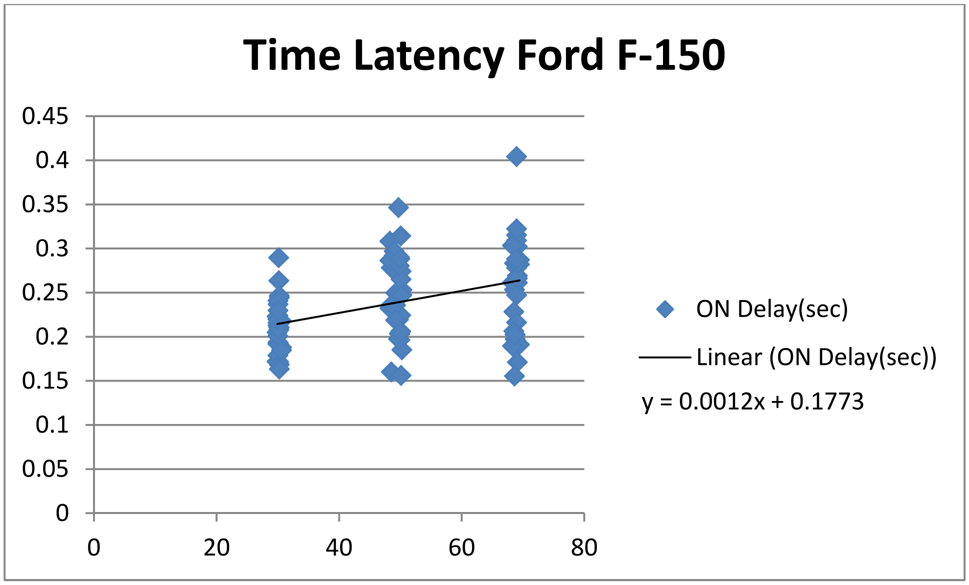


Figure 55. Time Latency (sec) versus Speed (mph) for F-150.

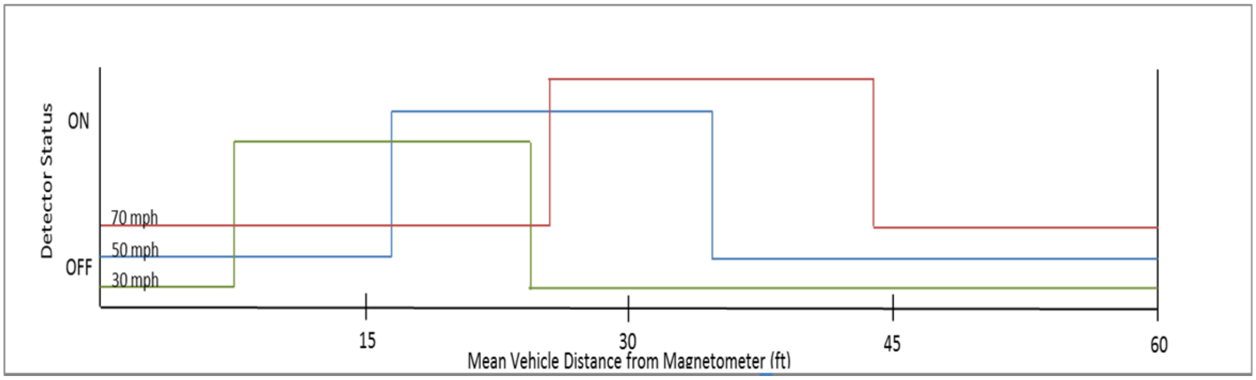


Figure 56. Trace of Mean Vehicle Distance from Magnetometer for F-150.

Dodge Minivan

Table 50. Detector On Delay Stats for Dodge Minivan.

	n	Mean	Variance	Std. dev.	Std. err.	Median	Range	Min	Max
All Speeds	90	19.05	62.84	7.93	0.84	18.92	30.56	6.98	37.55
30 mph	30	10.54	6.53	2.56	0.47	10.13	8.49	6.98	15.47
50 mph	30	18.40	11.18	3.34	0.61	19.27	11.90	12.56	24.47
70 mph	30	28.21	12.92	3.59	0.66	28.35	20.94	16.60	37.55

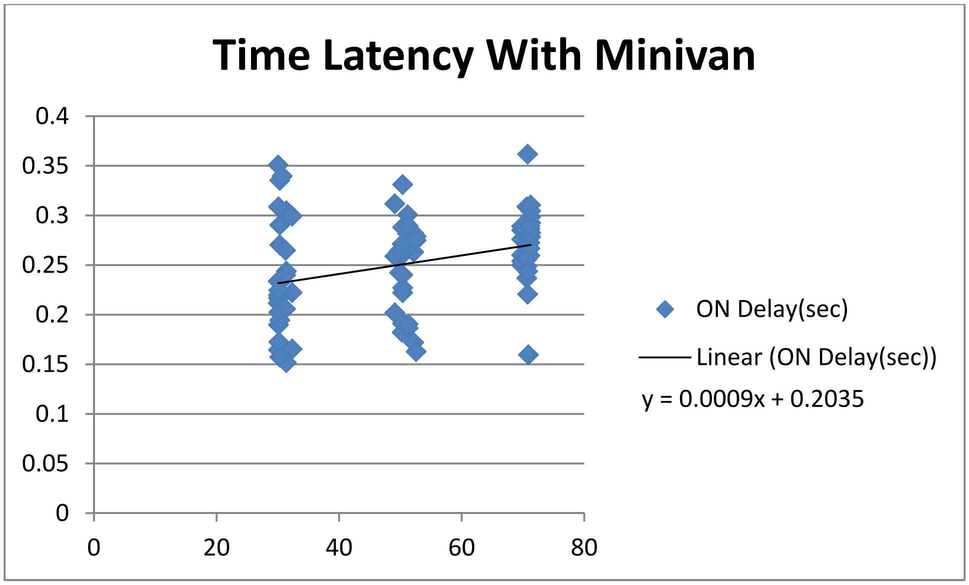


Figure 57. Time Latency (sec) versus Speed (mph) for Dodge Minivan.

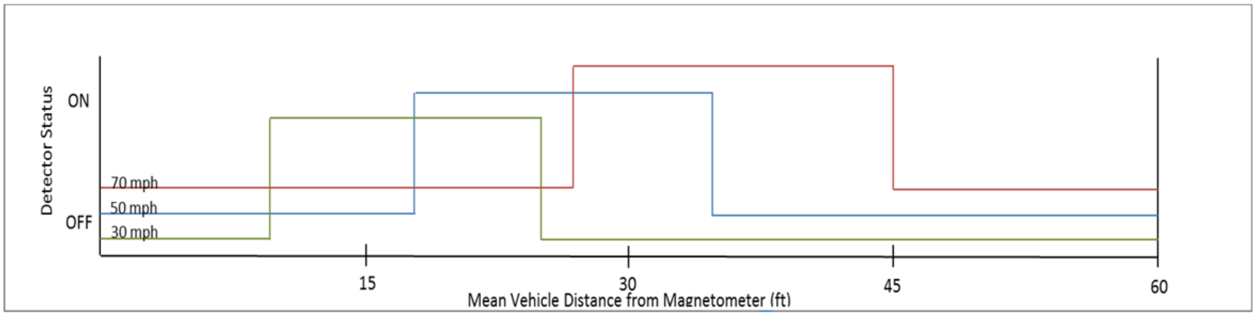


Figure 58. Trace of Mean Vehicle Distance from Magnetometer for Dodge Minivan.

Toyota Highlander

Table 51. Detector On Delay Stats for Toyota Highlander.

	n	Mean	Variance	Std. dev.	Std. err.	Median	Range	Min	Max
All Speeds	90	16.06	50.10	7.08	0.75	15.63	28.76	5.70	34.47
30 mph	30	8.48	2.08	1.44	0.26	8.21	6.02	5.70	11.72
50 mph	30	15.65	8.16	2.86	0.52	15.63	11.70	10.88	22.58
70 mph	30	24.04	17.89	4.23	0.77	23.42	18.44	16.03	34.47

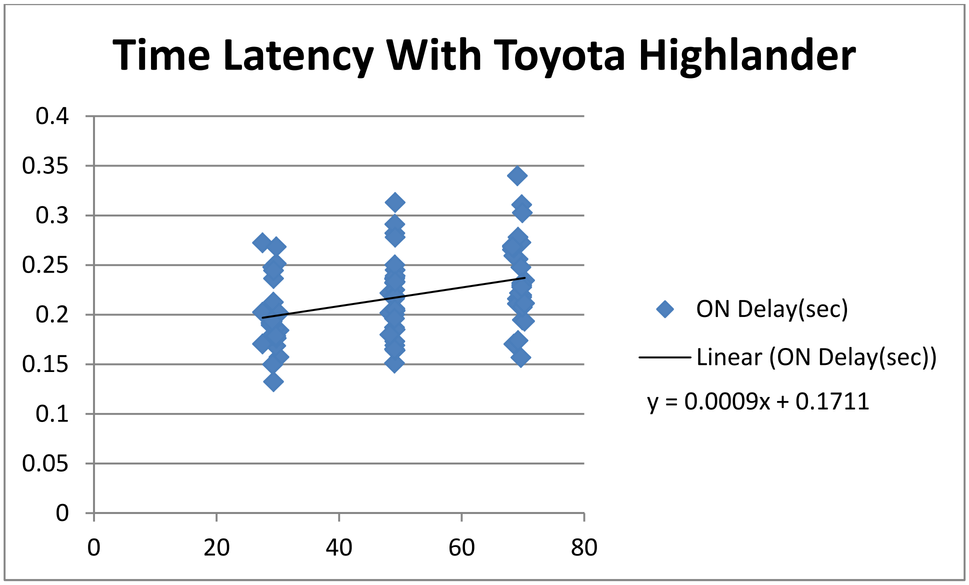


Figure 59. Time Latency (sec) versus Speed (mph) for Toyota Highlander.

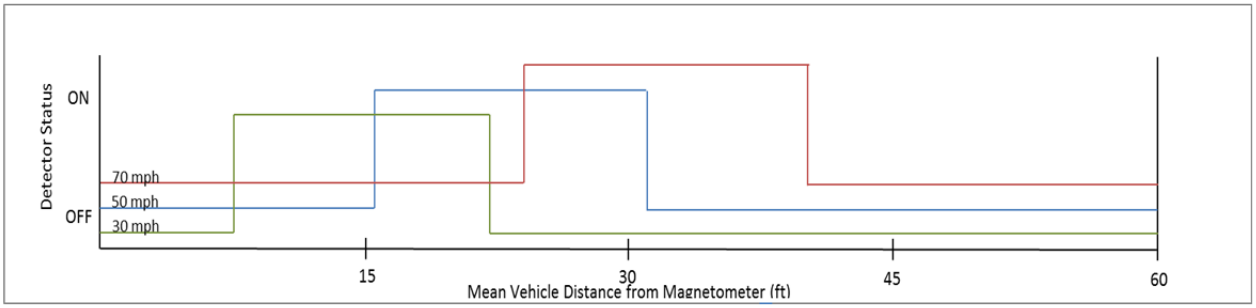


Figure 60. Trace of Mean Vehicle Distance from Magnetometer for Toyota Highlander.

Freightliner Class 8 Truck Tractor

Table 52. Detector On Delay Stats for Freightliner.

	n	Mean	Variance	Std. dev.	Std. err.	Median	Range	Min	Max
All Speeds	55	22.09	72.15	8.49	1.15	20.72	36.06	11.10	47.16
50 mph	28	21.82	134.89	11.61	2.19	17.05	36.06	11.10	47.16
70 mph	27	22.36	9.62	3.10	0.60	21.62	12.08	15.83	27.91

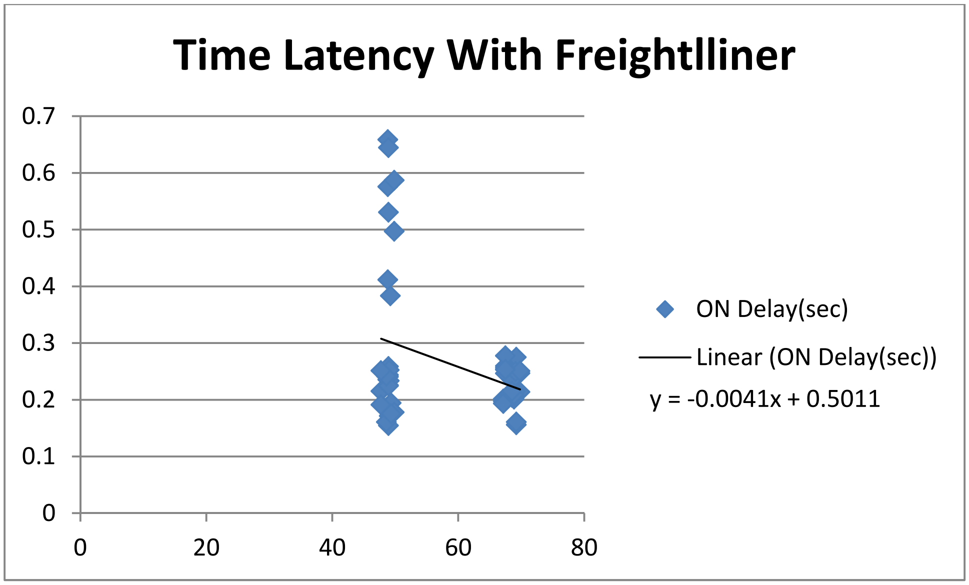


Figure 61. Time Latency (sec) versus Speed (mph) for Freightliner.

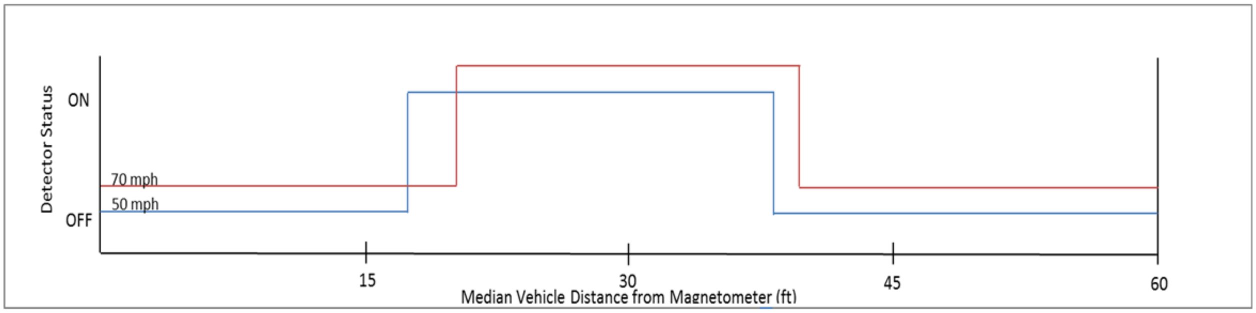


Figure 62. Trace of Mean Vehicle Distance from Magnetometer for Freightliner.

Note: Median values are used in this chart because mean value is skewed by an outlier in "Detector Off Delay"

Ford F-250 (Four-Wheel Drive Pickup)

Table 53. Detector On Delay Stats for Ford F-250.

	n	Mean	Variance	Std. dev.	Std. err.	Median	Range	Min	Max
All Speeds	45	20.04	98.58	9.93	1.48	22.25	39.95	0.83	40.78
50 mph	18	14.76	74.26	8.62	2.03	16.66	24.31	0.83	25.14
70 mph	27	23.55	86.16	9.28	1.79	26.12	33.39	7.39	40.78

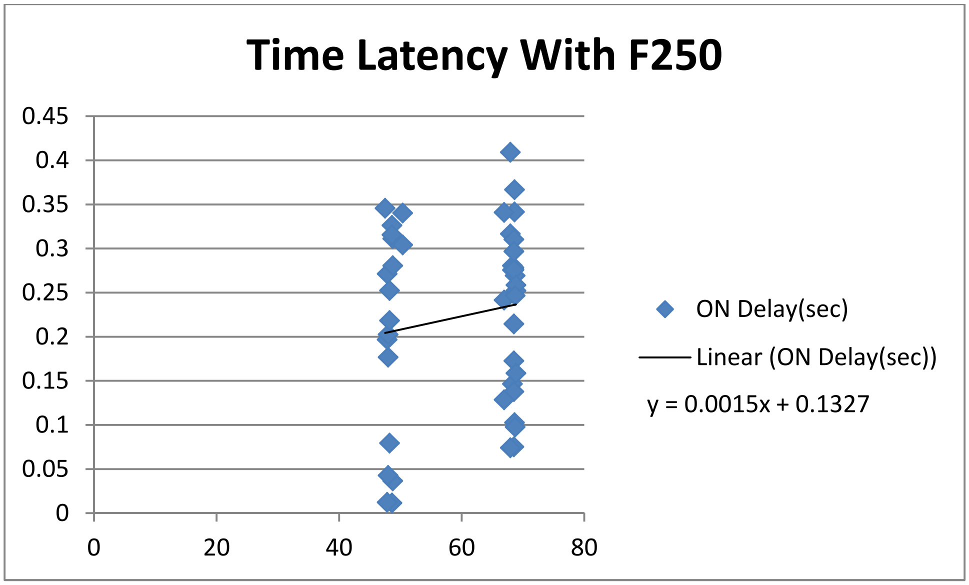


Figure 63. Time Latency (sec) versus Speed (mph) for Ford F-250.

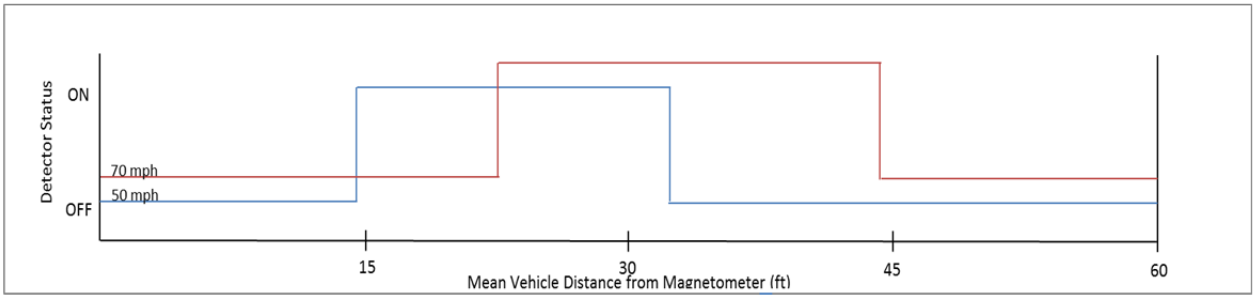


Figure 64. Trace of Mean Vehicle Distance from Magnetometer for Ford F-250.

Ford Fusion

Table 54. Detector On Delay Stats for Ford Fusion.

	n	Mean	Variance	Std. dev.	Std. err.	Median	Range	Min	Max
All Speeds	45	19.65	22.09	4.70	0.70	19.27	20.03	9.21	29.24
50 mph	18	15.74	10.59	3.25	0.77	15.80	11.65	9.21	20.87
70 mph	27	22.27	12.73	3.57	0.69	22.72	14.99	14.25	29.24

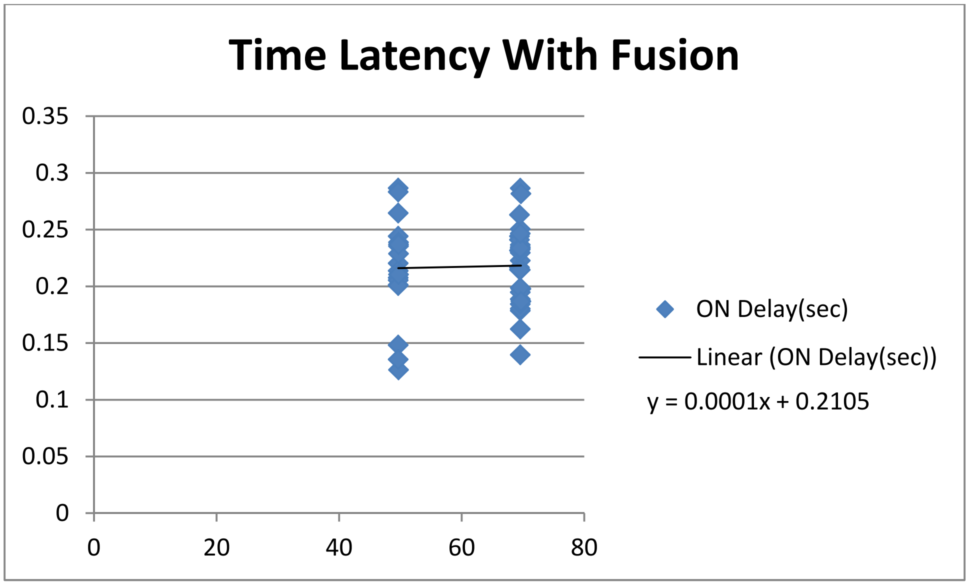


Figure 65. Time Latency (sec) versus Speed (mph) for Ford Fusion.

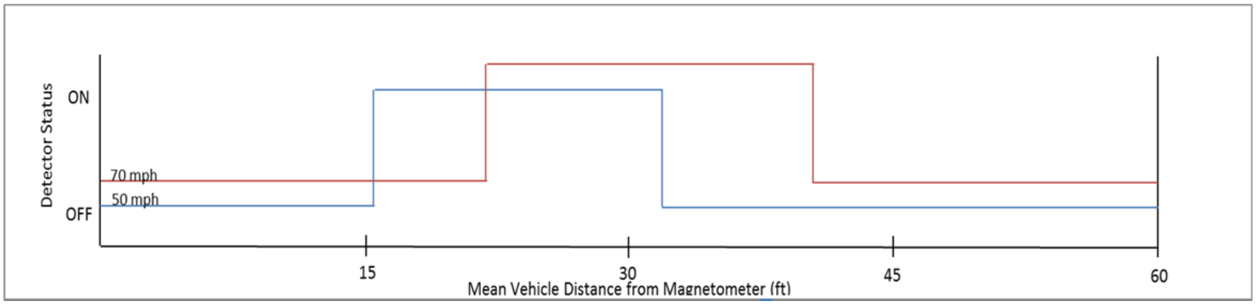


Figure 66. Trace of Mean Vehicle Distance from Magnetometer for Ford Fusion.

INTERPRETATION

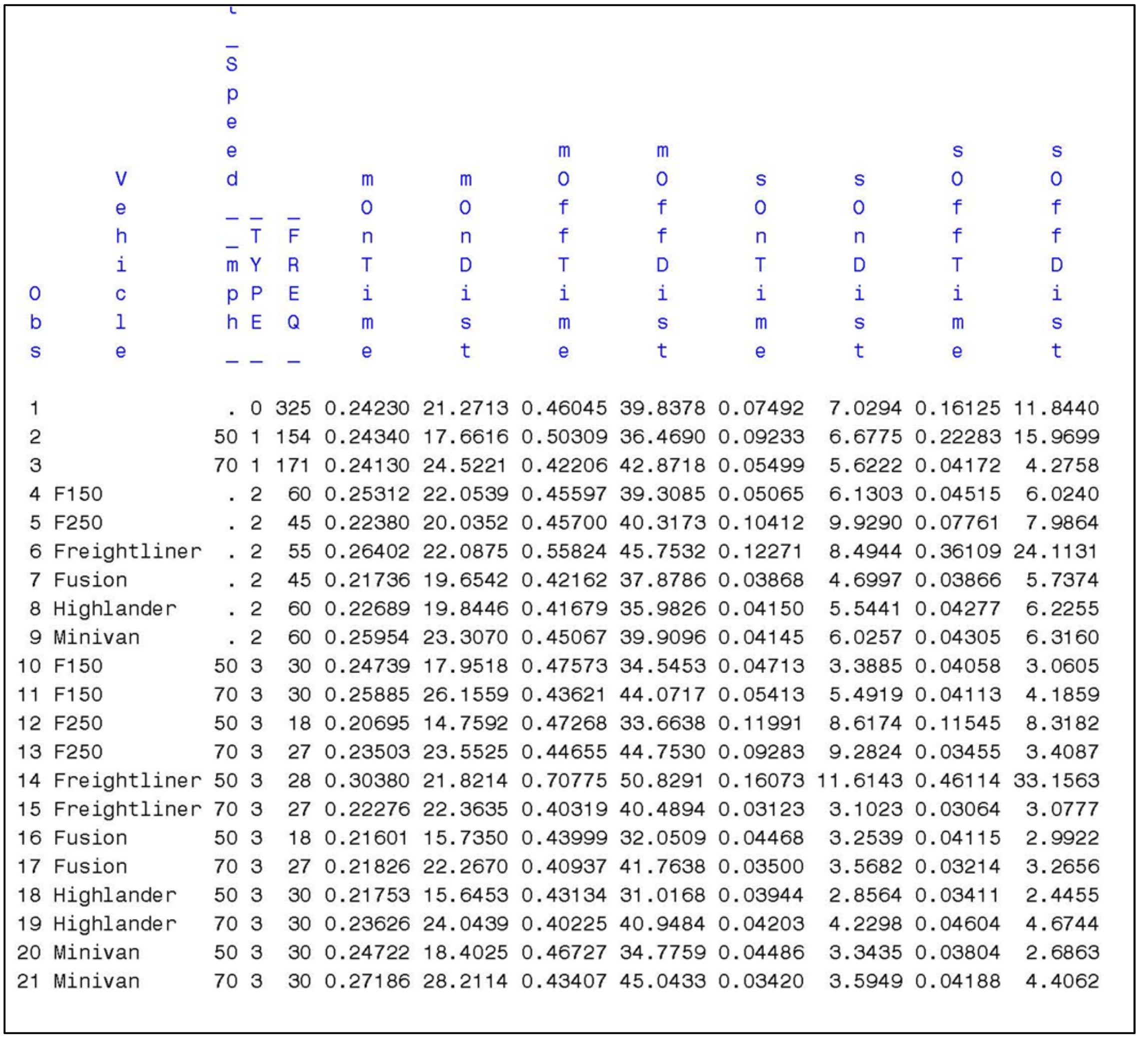
TTI assembled the observations for the six vehicles into one master file and imported it into SAS and then ran some summary statistics. The statistics shown in Figure 67 result from observations for 50-mph and 70-mph tests. Findings indicate that there is no significant difference between vehicles, so the same correction factor can be applied to all vehicles. Considering only time delay (and not distance delay), the pods performed about the same for 50 and 70 mph. Specifically, they give about a 0.24-sec delay for the on time and 0.46-sec delay for the off time, with standard deviations of 0.075 sec and 0.161 sec, respectively. The distance delays are different across the speeds as expected.

TTI then corrected its Excel spreadsheet and moved forward with correction factors of 0.24 sec for on times and 0.46 sec for off times. Having one correction factor for on and another for off, instead of having to use separate factors for each combination of speed, vehicle, and detector status (on/off) facilitated quicker change to the spreadsheet process.

The SAS variables in Figure 67 are as follows:

mOnTime = mean time delay for on observations.
mOnDist = mean distance delay for on observations.

mOffTime = mean time delay for off observations.
mOffDist = mean distance delay for off observations.
sOnTime = standard deviation of time delay for on observations.
sOnDist = standard deviation of distance delay for on observations.
sOffTime = standard deviation of time delay for off observations.
sOffDist = standard deviation of distance delay for off observations.



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                 t
                 _
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                 e                          m       m                       s       s
        V        d          m       m       O       O       s       s       O       O
        e        _ _  _     O       O       f       f       O       O       f       f
        h        _ T  F     n       n       f       f       n       n       f       f
        i        m Y  R     T       D       T       D       T       D       T       D
 O      c        p P  E     i       i       i       i       i       i       i       i
 b      l        h E  Q     m       s       m       s       m       s       m       s
 s      e        _ _  _     e       t       e       t       e       t       e       t

 1               . 0  325 0.24230 21.2713 0.46045 39.8378 0.07492  7.0294 0.16125 11.8440
 2              50 1  154 0.24340 17.6616 0.50309 36.4690 0.09233  6.6775 0.22283 15.9699
 3              70 1  171 0.24130 24.5221 0.42206 42.8718 0.05499  5.6222 0.04172  4.2758
 4 F150          . 2   60 0.25312 22.0539 0.45597 39.3085 0.05065  6.1303 0.04515  6.0240
 5 F250          . 2   45 0.22380 20.0352 0.45700 40.3173 0.10412  9.9290 0.07761  7.9864
 6 Freightliner  . 2   55 0.26402 22.0875 0.55824 45.7532 0.12271  8.4944 0.36109 24.1131
 7 Fusion        . 2   45 0.21736 19.6542 0.42162 37.8786 0.03868  4.6997 0.03866  5.7374
 8 Highlander    . 2   60 0.22689 19.8446 0.41679 35.9826 0.04150  5.5441 0.04277  6.2255
 9 Minivan       . 2   60 0.25954 23.3070 0.45067 39.9096 0.04145  6.0257 0.04305  6.3160
10 F150         50 3   30 0.24739 17.9518 0.47573 34.5453 0.04713  3.3885 0.04058  3.0605
11 F150         70 3   30 0.25885 26.1559 0.43621 44.0717 0.05413  5.4919 0.04113  4.1859
12 F250         50 3   18 0.20695 14.7592 0.47268 33.6638 0.11991  8.6174 0.11545  8.3182
13 F250         70 3   27 0.23503 23.5525 0.44655 44.7530 0.09283  9.2824 0.03455  3.4087
14 Freightliner 50 3   28 0.30380 21.8214 0.70775 50.8291 0.16073 11.6143 0.46114 33.1563
15 Freightliner 70 3   27 0.22276 22.3635 0.40319 40.4894 0.03123  3.1023 0.03064  3.0777
16 Fusion       50 3   18 0.21601 15.7350 0.43999 32.0509 0.04468  3.2539 0.04115  2.9922
17 Fusion       70 3   27 0.21826 22.2670 0.40937 41.7638 0.03500  3.5682 0.03214  3.2656
18 Highlander   50 3   30 0.21753 15.6453 0.43134 31.0168 0.03944  2.8564 0.03411  2.4455
19 Highlander   70 3   30 0.23626 24.0439 0.40225 40.9484 0.04203  4.2298 0.04604  4.6744
20 Minivan      50 3   30 0.24722 18.4025 0.46727 34.7759 0.04486  3.3435 0.03804  2.6863
21 Minivan      70 3   30 0.27186 28.2114 0.43407 45.0433 0.03420  3.5949 0.04188  4.4062
```

Figure 67. SAS Output for Tapeswitch Data.

HIGH-SPEED VIDEOGRAPHY

Introduction

One additional verification technique used in this research to corroborate other findings related to Pod activations/deactivations was to use a high-speed video camera coupled with the Trafficware Pods to monitor passage of the Toyota Highlander at 50 mph and 70 mph. For this procedure, TTI developed a program that provided a visual indication of the Pod on that was captured on video as the vehicle passed the detection point.

Procedure

Figure 68 and Figure 69 are screen captures that also show the user interface available from the company, AMETEK, for operating the video system on-site. The software allows selection of functions such as forward, reverse, fast-forward, pause, and stop. This video was captured at 50 mph to demonstrate the procedure. Prior to beginning the video recording process, a TTI photographic expert set up the camera aimed at a 90-degree angle to the direction of the lane so that it could capture the side of the vehicle.

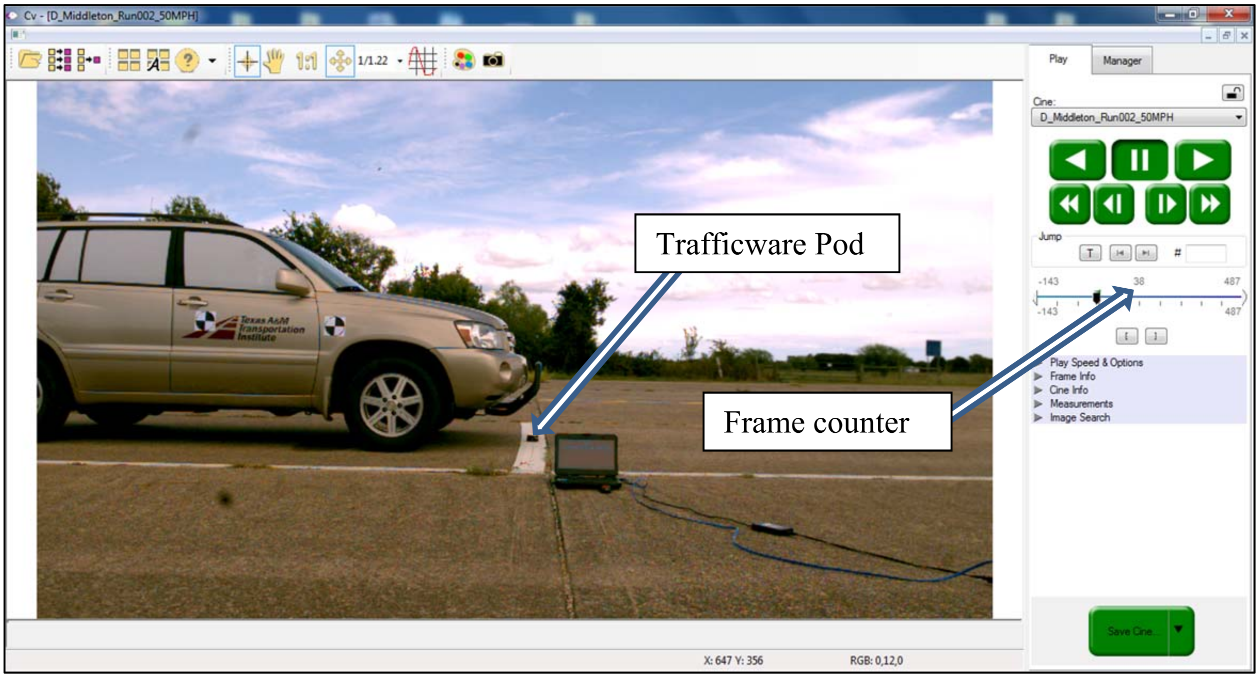
TTI placed two targets on the vehicle's right side at 3.0 ft spacing to be used for accurately determining the car's exact position during video playback. The other component of this test was a means to record exactly when the Pod activated upon arrival of the car. A laptop placed in the field of view of the same high-speed camera provided this visual cue. The TTI program caused the laptop screen to turn white upon activation of the Pod so the user can determine the instant the Pod activates and where the vehicle is located in relation to the Pod.

As the Toyota Highlander approached the recording zone, the TTI specialist began recording a 4.0-sec recording of the vehicle passage at a frame rate of 1,000 frames per second. The camera expert manually started recording just before the front of the vehicle arrived over the Pod. Using the camera software, the user is able to replay the recorded video and establish the moment in time that the front of the vehicle began passing over the Pod, the moment when the rear of the vehicle passed the Pod, and the instant the Pod activated to indicate a presence detection.

Interpretation of Video Results

In Figure 68, the frame associated with the front of the Highlander is frame no. 38 and in Figure 69 the frame associated with the Pod activation is no. 321. The difference in the two values is an indication of the latency of the Pod activation, or 283 milliseconds. A full understanding of the latency characteristics would require a larger dataset such as the one collected by the tapeswitches, but this verification at least supports that finding.

For this project, the latency is acceptable as long as it is consistent and properly compensated so that its effect is minimal. The correction that was found to apply to this and other vehicles and to both 50 mph and 70 mph was 240 milliseconds. As noted elsewhere, the corrected results apply the 0.24 sec on both the activation and the deactivation.


Trafficware Pod

Frame counter

Figure 68. Photo Showing Front of Vehicle over Pod.

Figure 69. Photo Showing Laptop Monitor Turning White to Indicate Pod Activating.

APPENDIX C. RAW DETECTOR DATA SUMMARY

Table 55. Summary Counts for 50 mph Day, Dry.

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	401	19	1	21	2	354
Iteris Stop Line	SB13	243	10	1	2	41	185
Iteris Tripline at 485 ft	SB15	243	50	3	0	0	192
Iteris Tripline at 566 ft	SB16	0	0	0	0	0	0
Wavetronix Matrix	SB17	77	0	0	1	2	75
Wavetronix Advance	SB21	77	0	0	4	2	73
Aldis Upstream	SB38	603	54	298	25	154	455
Aldis Stop Line	SB46	603	128	19	36	22	422
Pod 100 ft from stop line	SB51	487	18	2	22	1	444
Pod 200 ft from stop line	SB52	487	20	3	21	2	440
Pod 300 ft from stop line	SB53	487	19	4	22	1	440
Pod 400 ft from stop line	SB54	487	18	4	18	0	445
Pod 500 ft from stop line	SB55	487	18	7	19	1	440
Pod 600 ft from stop line	SB56	487	19	11	30	1	423
Pod 700 ft from stop line	SB57	487	18	11	20	0	435
Pod 800 ft from stop line	SB58	487	20	20	16	0	428
Pod at stop line	SB59	487	18	1	14	1	452
	Total	6630	429	385	271	230	5703

Table 56. Summary Percents for 50 mph Day, Dry.

Detector	Channel	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	4.74%	0.25%	5.24%	0.50%	94.01%
Iteris Stop Line	SB13	4.12%	0.41%	0.82%	16.87%	93.83%
Iteris Tripline at 485 ft	SB15	20.58%	1.23%	0.00%	0.00%	79.01%
Iteris Tripline at 566 ft	SB16					
Wavetronix Matrix	SB17	0.00%	0.00%	1.30%	2.60%	101.30%
Wavetronix Advance	SB21	0.00%	0.00%	5.19%	2.60%	94.81%
Aldis Upstream	SB38	8.96%	49.42%	4.15%	25.54%	75.46%
Aldis Stop Line	SB46	21.23%	3.15%	5.97%	3.65%	79.60%
Pod 100 ft from stop line	SB51	3.70%	0.41%	4.52%	0.21%	91.17%
Pod 200 ft from stop line	SB52	4.11%	0.62%	4.31%	0.41%	90.35%
Pod 300 ft from stop line	SB53	3.90%	0.82%	4.52%	0.21%	90.35%
Pod 400 ft from stop line	SB54	3.70%	0.82%	3.70%	0.00%	91.38%
Pod 500 ft from stop line	SB55	3.70%	1.44%	3.90%	0.21%	90.35%
Pod 600 ft from stop line	SB56	3.90%	2.26%	6.16%	0.21%	86.86%
Pod 700 ft from stop line	SB57	3.70%	2.26%	4.11%	0.00%	89.32%
Pod 800 ft from stop line	SB58	4.11%	4.11%	3.29%	0.00%	87.89%
Pod at stop line	SB59	3.70%	0.21%	2.87%	0.21%	92.81%
	Total	6.47%	5.81%	4.09%	3.47%	87.84%

Table 57. Summary Counts for 50 mph Transition, Dry.

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	47	0	0	0	0	45
Iteris Stop Line	SB13	30	0	0	0	1	29
Iteris Tripline at 485 ft	SB15	30	1	0	0	1	28
Iteris Tripline at 566 ft	SB16	0	0	0	0	0	0
Wavetronix Matrix	SB17	0	0	0	0	0	0
Wavetronix Advance	SB21	0	0	0	0	0	0
Aldis Upstream	SB38	121	37	21	0	19	82
Aldis Stop Line	SB46	121	13	1	8	4	94
Pod 100 ft from stop line	SB51	121	0	0	0	0	120
Pod 200 ft from stop line	SB52	121	1	0	1	0	118
Pod 300 ft from stop line	SB53	121	0	0	1	0	119
Pod 400 ft from stop line	SB54	121	1	0	2	0	118
Pod 500 ft from stop line	SB55	121	2	1	0	0	118
Pod 600 ft from stop line	SB56	121	1	1	2	1	116
Pod 700 ft from stop line	SB57	121	2	2	0	0	117
Pod 800 ft from stop line	SB58	121	2	4	0	0	115
Pod at stop line	SB59	121	1	0	2	0	117
	Total	1438	61	30	16	26	1336

Table 58. Summary Percents for 50 mph Transition, Dry.

Detector	Channel	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	0.00%	0.00%	0.00%	0.00%	95.74%
Iteris Stop Line	SB13	0.00%	0.00%	0.00%	3.33%	100.00%
Iteris Tripline at 485 ft	SB15	3.33%	0.00%	0.00%	3.33%	93.33%
Iteris Tripline at 566 ft	SB16					
Wavetronix Matrix	SB17					
Wavetronix Advance	SB21					
Aldis Upstream	SB38	30.58%	17.36%	0.00%	15.70%	67.77%
Aldis Stop Line	SB46	10.74%	0.83%	6.61%	3.31%	87.60%
Pod 100 ft from stop line	SB51	0.00%	0.00%	0.00%	0.00%	99.17%
Pod 200 ft from stop line	SB52	0.83%	0.00%	0.83%	0.00%	97.52%
Pod 300 ft from stop line	SB53	0.00%	0.00%	0.83%	0.00%	98.35%
Pod 400 ft from stop line	SB54	0.83%	0.00%	1.65%	0.00%	97.52%
Pod 500 ft from stop line	SB55	1.65%	0.83%	0.00%	0.00%	97.52%
Pod 600 ft from stop line	SB56	0.83%	0.83%	1.65%	0.83%	95.87%
Pod 700 ft from stop line	SB57	1.65%	1.65%	0.00%	0.00%	96.69%
Pod 800 ft from stop line	SB58	1.65%	3.31%	0.00%	0.00%	95.04%
Pod at stop line	SB59	0.83%	0.00%	1.65%	0.00%	96.69%
	Total	4.24%	2.09%	1.11%	1.81%	91.41%

Table 59. Summary Counts for 50 mph Night, Dry

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	215	5	0	1	0	210
Iteris Stop Line	SB13	0	0	0	0	0	0
Iteris Tripline at 485 ft	SB15	0	0	0	0	0	0
Iteris Tripline at 566 ft	SB16	0	0	0	0	0	0
Wavetronix Matrix	SB17	41	0	1	0	1	39
Wavetronix Advance	SB21	41	0	1	0	0	40
Aldis Upstream	SB38	91	2	0	0	0	90
Aldis Stop Line	SB46	215	5	1	0	0	211
Pod 100 ft from stop line	SB51	215	2	0	3	0	211
Pod 200 ft from stop line	SB52	215	3	0	0	0	213
Pod 300 ft from stop line	SB53	215	3	0	3	0	210
Pod 400 ft from stop line	SB54	215	2	2	1	0	210
Pod 500 ft from stop line	SB55	215	2	5	3	0	205
Pod 600 ft from stop line	SB56	215	2	7	3	0	203
Pod 700 ft from stop line	SB57	215	3	7	0	0	205
Pod 800 ft from stop line	SB58	215	5	12	1	0	197
Pod at stop line	SB59	215	4	0	1	1	210
	Total	2538	38	36	16	2	2454

Table 60. Summary Percents for 50 mph Night, Dry.

Detector	Channel	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	2.33%	0.00%	0.47%	0.00%	98.14%
Iteris Stop Line	SB13					
Iteris Tripline at 485 ft	SB15					
Iteris Tripline at 566 ft	SB16					
Wavetronix Matrix	SB17	0.00%	2.44%	0.00%	2.44%	97.56%
Wavetronix Advance	SB21	0.00%	2.44%	0.00%	0.00%	97.56%
Aldis Upstream	SB38	2.20%	0.00%	0.00%	0.00%	98.90%
Aldis Stop Line	SB46	2.33%	0.47%	0.00%	0.00%	98.14%
Pod 100 ft from stop line	SB51	0.93%	0.00%	1.40%	0.00%	98.14%
Pod 200 ft from stop line	SB52	1.40%	0.00%	0.00%	0.00%	99.07%
Pod 300 ft from stop line	SB53	1.40%	0.00%	1.40%	0.00%	97.67%
Pod 400 ft from stop line	SB54	0.93%	0.93%	0.47%	0.00%	97.67%
Pod 500 ft from stop line	SB55	0.93%	2.33%	1.40%	0.00%	95.35%
Pod 600 ft from stop line	SB56	0.93%	3.26%	1.40%	0.00%	94.42%
Pod 700 ft from stop line	SB57	1.40%	3.26%	0.00%	0.00%	95.35%
Pod 800 ft from stop line	SB58	2.33%	5.58%	0.47%	0.00%	91.63%
Pod at stop line	SB59	1.86%	0.00%	0.47%	0.47%	97.67%
	Total	1.50%	1.42%	0.63%	0.08%	98.09%

Table 61. Summary Counts for 50 mph Day, Rain.

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	172	3	3	49	0	119
Iteris Stop Line	SB13	42	12	0	3	1	26
Iteris Tripline at 485 ft	SB15	42	2	0	0	0	40
Iteris Tripline at 566 ft	SB16	0	0	0	0	0	0
Wavetronix Matrix	SB17	29	0	0	0	2	29
Wavetronix Advance	SB21	29	0	0	1	0	28
Aldis Upstream	SB38	232	0	232	3	84	199
Aldis Stop Line	SB46	232	0	2	29	2	202
Pod 100 ft from stop line	SB51	232	1	2	14	0	215
Pod 200 ft from stop line	SB52	232	0	0	11	0	221
Pod 300 ft from stop line	SB53	232	0	0	14	0	218
Pod 400 ft from stop line	SB54	232	2	1	15	0	214
Pod 500 ft from stop line	SB55	232	0	4	9	0	219
Pod 600 ft from stop line	SB56	232	0	13	16	0	203
Pod 700 ft from stop line	SB57	232	0	10	12	0	210
Pod 800 ft from stop line	SB58	232	0	20	7	0	205
Pod at stop line	SB59	232	0	0	19	0	213
	Total	2866	20	287	202	89	2561

Table 62. Summary Percents for 50 mph Day, Rain.

Detector	Channel	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	1.74%	1.74%	28.49%	0.00%	97.67%
Iteris Stop Line	SB13	28.57%	0.00%	7.14%	2.38%	71.43%
Iteris Tripline at 485 ft	SB15	4.76%	0.00%	0.00%	0.00%	95.24%
Iteris Tripline at 566 ft	SB16					
Wavetronix Matrix	SB17	0.00%	0.00%	0.00%	6.90%	106.90%
Wavetronix Advance	SB21	0.00%	0.00%	3.45%	0.00%	96.55%
Aldis Upstream	SB38	0.00%	100.00%	1.29%	36.21%	85.78%
Aldis Stop Line	SB46	0.00%	0.86%	12.50%	0.86%	100.43%
Pod 100 ft from stop line	SB51	0.43%	0.86%	6.03%	0.00%	92.67%
Pod 200 ft from stop line	SB52	0.00%	0.00%	4.74%	0.00%	95.26%
Pod 300 ft from stop line	SB53	0.00%	0.00%	6.03%	0.00%	93.97%
Pod 400 ft from stop line	SB54	0.86%	0.43%	6.47%	0.00%	92.24%
Pod 500 ft from stop line	SB55	0.00%	1.72%	3.88%	0.00%	94.40%
Pod 600 ft from stop line	SB56	0.00%	5.60%	6.90%	0.00%	87.50%
Pod 700 ft from stop line	SB57	0.00%	4.31%	5.17%	0.00%	90.52%
Pod 800 ft from stop line	SB58	0.00%	8.62%	3.02%	0.00%	88.36%
Pod at stop line	SB59	0.00%	0.00%	8.19%	0.00%	91.81%
	Total	0.70%	10.01%	7.05%	3.11%	97.26%

Table 63. Summary Counts for 70 mph Day, Dry.

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	268	4	6	1	1	259
Iteris Stop Line	SB13	66	14	0	2	24	26
Iteris Tripline at 485 ft	SB15	66	8	0	0	0	58
Iteris Tripline at 566 ft	SB16	66	40	0	0	0	26
Wavetronix Matrix	SB17	48	1	0	0	6	41
Wavetronix Advance	SB21	48	0	0	0	2	47
Aldis Upstream	SB38	229	24	263	1	18	15
Aldis Stop Line	SB46	392	31	10	2	17	342
Pod 100 ft from stop line	SB51	294	3	1	1	2	288
Pod 200 ft from stop line	SB52	294	3	3	1	0	288
Pod 300 ft from stop line	SB53	294	0	6	0	0	289
Pod 400 ft from stop line	SB54	294	3	5	2	1	284
Pod 500 ft from stop line	SB55	294	3	6	2	1	283
Pod 600 ft from stop line	SB56	294	4	6	0	1	284
Pod 700 ft from stop line	SB57	294	0	7	0	1	287
Pod 800 ft from stop line	SB58	294	6	8	0	0	281
Pod at stop line	SB59	294	1	1	1	1	291
	Total	3829	145	322	13	75	3389

Table 64. Summary Percents for 70 mph Day, Dry.

Detector	**Channel**	**Miss**	**False**	**Stuck**	**Drop**	**Correct**
FLIR VIP Stop Line	SB5	1.49%	2.24%	0.37%	0.37%	97.39%
Iteris Stop Line	SB13	21.21%	0.00%	3.03%	36.36%	78.79%
Iteris Tripline at 485 ft	SB15	12.12%	0.00%	0.00%	0.00%	87.88%
Iteris Tripline at 566 ft	SB16	60.61%	0.00%	0.00%	0.00%	39.39%
Wavetronix Matrix	SB17	2.08%	0.00%	0.00%	12.50%	97.92%
Wavetronix Advance	SB21	0.00%	0.00%	0.00%	4.17%	97.92%
Aldis Upstream	SB38	10.48%	114.85%	0.44%	7.86%	6.55%
Aldis Stop Line	SB46	7.91%	2.55%	0.51%	4.34%	92.09%
Pod 100 ft from stop line	SB51	1.02%	0.34%	0.34%	0.68%	97.96%
Pod 200 ft from stop line	SB52	1.02%	1.02%	0.34%	0.00%	97.96%
Pod 300 ft from stop line	SB53	0.00%	2.04%	0.00%	0.00%	98.30%
Pod 400 ft from stop line	SB54	1.02%	1.70%	0.68%	0.34%	96.60%
Pod 500 ft from stop line	SB55	1.02%	2.04%	0.68%	0.34%	96.26%
Pod 600 ft from stop line	SB56	1.36%	2.04%	0.00%	0.34%	96.60%
Pod 700 ft from stop line	SB57	0.00%	2.38%	0.00%	0.34%	97.62%
Pod 800 ft from stop line	SB58	2.04%	2.72%	0.00%	0.00%	95.58%
Pod at stop line	SB59	0.34%	0.34%	0.34%	0.34%	98.98%
	Total	3.79%	8.41%	0.34%	1.96%	93.15%

Table 65. Summary Counts for 70 mph Transition, Dry.

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	0	0	0	0	0	0
Iteris Stop Line	SB13	33	0	0	0	28	5
Iteris Tripline at 485 ft	SB15	33	8	0	0	1	24
Iteris Tripline at 566 ft	SB16	33	9	0	0	0	24
Wavetronix Matrix	SB17	0	0	0	0	0	0
Wavetronix Advance	SB21	0	0	0	0	0	0
Aldis Upstream	SB38	33	0	255	0	28	0
Aldis Stop Line	SB46	33	0	0	0	0	33
Pod 100 ft from stop line	SB51	33	0	0	0	0	33
Pod 200 ft from stop line	SB52	33	0	0	0	0	33
Pod 300 ft from stop line	SB53	33	0	0	0	0	33
Pod 400 ft from stop line	SB54	33	0	0	0	0	33
Pod 500 ft from stop line	SB55	33	0	1	0	0	32
Pod 600 ft from stop line	SB56	33	0	0	0	0	33
Pod 700 ft from stop line	SB57	33	0	0	0	0	33
Pod 800 ft from stop line	SB58	33	0	0	0	0	33
Pod at stop line	SB59	33	0	0	0	0	33
	Total	462	17	256	24	57	382

Table 66. Summary Percents for 70 mph Transition, Dry.

Detector	Channel	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5					
Iteris Stop Line	SB13	0.00%	0.00%	0.00%	84.85%	100.00%
Iteris Tripline at 485 ft	SB15	24.24%	0.00%	0.00%	3.03%	72.73%
Iteris Tripline at 566 ft	SB16	27.27%	0.00%	0.00%	0.00%	72.73%
Wavetronix Matrix	SB17					
Wavetronix Advance	SB21					
Aldis Upstream	SB38	0.00%	772.73%	0.00%	84.85%	0.00%
Aldis Stop Line	SB46	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 100 ft from stop line	SB51	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 200 ft from stop line	SB52	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 300 ft from stop line	SB53	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 400 ft from stop line	SB54	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 500 ft from stop line	SB55	0.00%	3.03%	0.00%	0.00%	96.97%
Pod 600 ft from stop line	SB56	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 700 ft from stop line	SB57	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 800 ft from stop line	SB58	0.00%	0.00%	0.00%	0.00%	100.00%
Pod at stop line	SB59	0.00%	0.00%	0.00%	0.00%	100.00%
	Total	3.68%	55.41%	5.19%	12.34%	100.00%

Table 67. Summary Counts for 70 mph Night, Dry.

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	180	1	7	2	0	177
Iteris Stop Line	SB13	0	0	0	0	0	0
Iteris Tripline at 485 ft	SB15	0	0	0	0	0	0
Iteris Tripline at 566 ft	SB16	0	0	0	0	0	0
Wavetronix Matrix	SB17	0	0	0	0	0	0
Wavetronix Advance	SB21	0	0	0	0	0	0
Aldis Upstream	SB38	180	0	1	0	0	180
Aldis Stop Line	SB46	180	0	1	0	0	180
Pod 100 ft from stop line	SB51	180	0	1	0	0	179
Pod 200 ft from stop line	SB52	180	1	1	1	1	177
Pod 300 ft from stop line	SB53	180	0	1	0	0	180
Pod 400 ft from stop line	SB54	180	0	1	0	1	179
Pod 500 ft from stop line	SB55	180	0	1	0	0	180
Pod 600 ft from stop line	SB56	180	0	1	0	1	179
Pod 700 ft from stop line	SB57	180	0	1	0	0	180
Pod 800 ft from stop line	SB58	180	1	2	0	0	178
Pod at stop line	SB59	180	2	0	0	0	178
	Total	2160	5	18	3	3	2147

Table 68. Summary Percents for 70 mph Night, Dry.

Detector	Channel	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	0.56%	3.89%	1.11%	0.00%	99.44%
Iteris Stop Line	SB13					
Iteris Tripline at 485 ft	SB15					
Iteris Tripline at 566 ft	SB16					
Wavetronix Matrix	SB17					
Wavetronix Advance	SB21					
Aldis Upstream	SB38	0.00%	0.56%	0.00%	0.00%	100.00%
Aldis Stop Line	SB46	0.00%	0.56%	0.00%	0.00%	100.00%
Pod 100 ft from stop line	SB51	0.00%	0.56%	0.00%	0.00%	99.44%
Pod 200 ft from stop line	SB52	0.56%	0.56%	0.56%	0.56%	98.33%
Pod 300 ft from stop line	SB53	0.00%	0.56%	0.00%	0.00%	100.00%
Pod 400 ft from stop line	SB54	0.00%	0.56%	0.00%	0.56%	99.44%
Pod 500 ft from stop line	SB55	0.00%	0.56%	0.00%	0.00%	100.00%
Pod 600 ft from stop line	SB56	0.00%	0.56%	0.00%	0.56%	99.44%
Pod 700 ft from stop line	SB57	0.00%	0.56%	0.00%	0.00%	100.00%
Pod 800 ft from stop line	SB58	0.56%	1.11%	0.00%	0.00%	98.89%
Pod at stop line	SB59	1.11%	0.00%	0.00%	0.00%	98.89%
	Total	0.23%	0.83%	0.14%	0.14%	99.72%

Table 69. Summary Counts for 70 mph Day, Rain.

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	69	0	4	14	0	52
Iteris Stop Line	SB13	39	39	0	0	0	0
Iteris Tripline at 485 ft	SB15	39	16	0	1	0	22
Iteris Tripline at 566 ft	SB16	39	20	0	0	0	19
Wavetronix Matrix	SB17	30	3	0	0	3	24
Wavetronix Advance	SB21	30	0	0	1	0	29
Aldis Upstream	SB38	69	1	86	1	2	0
Aldis Stop Line	SB46	69	0	0	0	0	69
Pod 100 ft from stop line	SB51	69	0	0	0	0	69
Pod 200 ft from stop line	SB52	69	0	0	0	0	69
Pod 300 ft from stop line	SB53	69	0	0	0	1	68
Pod 400 ft from stop line	SB54	69	0	0	0	1	68
Pod 500 ft from stop line	SB55	69	0	0	0	2	67
Pod 600 ft from stop line	SB56	69	0	0	0	0	69
Pod 700 ft from stop line	SB57	69	1	0	1	0	67
Pod 800 ft from stop line	SB58	69	0	0	0	0	69
Pod at stop line	SB59	69	1	0	0	0	68
	Total	1005	81	90	18	9	829

Table 70. Summary Percents for 70 mph Day, Rain.

Detector	Channel	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	0.00%	5.80%	20.29%	0.00%	95.65%
Iteris Stop Line	SB13	100.00%	0.00%	0.00%	0.00%	0.00%
Iteris Tripline at 485 ft	SB15	41.03%	0.00%	2.56%	0.00%	56.41%
Iteris Tripline at 566 ft	SB16	51.28%	0.00%	0.00%	0.00%	48.72%
Wavetronix Matrix	SB17	10.00%	0.00%	0.00%	10.00%	90.00%
Wavetronix Advance	SB21	0.00%	0.00%	3.33%	0.00%	96.67%
Aldis Upstream	SB38	1.45%	124.64%	1.45%	2.90%	0.00%
Aldis Stop Line	SB46	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 100 ft from stop line	SB51	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 200 ft from stop line	SB52	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 300 ft from stop line	SB53	0.00%	0.00%	0.00%	1.45%	98.55%
Pod 400 ft from stop line	SB54	0.00%	0.00%	0.00%	1.45%	98.55%
Pod 500 ft from stop line	SB55	0.00%	0.00%	0.00%	2.90%	97.10%
Pod 600 ft from stop line	SB56	0.00%	0.00%	0.00%	0.00%	100.00%
Pod 700 ft from stop line	SB57	1.45%	0.00%	1.45%	0.00%	97.10%
Pod 800 ft from stop line	SB58	0.00%	0.00%	0.00%	0.00%	100.00%
Pod at stop line	SB59	1.45%	0.00%	0.00%	0.00%	98.55%
	Total	8.06%	8.96%	1.79%	0.90%	78.26%

Table 71. Summary Counts for All Speeds, All Light, All Weather Conditions.

Detector	Channel	Runs	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	1352	32	21	88	3	1216
Iteris Stop Line	SB13	453	75	1	7	95	271
Iteris Tripline at 485 ft	SB15	453	85	3	1	2	364
Iteris Tripline at 566 ft	SB16	138	69	0	0	0	69
Wavetronix Matrix	SB17	225	4	1	1	14	208
Wavetronix Advance	SB21	225	0	1	6	4	217
Aldis Upstream	SB38	1558	118	1156	30	305	1021
Aldis Stop Line	SB46	1845	177	34	75	45	1553
Pod 100 ft from stop line	SB51	1631	24	6	40	3	1559
Pod 200 ft from stop line	SB52	1631	28	7	35	3	1559
Pod 300 ft from stop line	SB53	1631	22	11	40	2	1557
Pod 400 ft from stop line	SB54	1631	26	13	38	3	1551
Pod 500 ft from stop line	SB55	1631	25	25	33	4	1544
Pod 600 ft from stop line	SB56	1631	26	39	51	4	1510
Pod 700 ft from stop line	SB57	1631	24	38	33	1	1534
Pod 800 ft from stop line	SB58	1631	34	66	24	0	1506
Pod at stop line	SB59	1631	27	2	37	3	1562
	Total	20928	796	1424	539	491	18801

Table 72. Summary Percents for All Speeds, All Light, All Weather Conditions.

Detector	Channel	Miss	False	Stuck	Drop	Correct
FLIR VIP Stop Line	SB5	2.37%	1.55%	6.51%	0.22%	96.67%
Iteris Stop Line	SB13	16.56%	0.22%	1.55%	20.97%	82.34%
Iteris Tripline at 485 ft	SB15	18.76%	0.66%	0.22%	0.44%	80.35%
Iteris Tripline at 566 ft	SB16	50.00%	0.00%	0.00%	0.00%	50.00%
Wavetronix Matrix	SB17	1.78%	0.44%	0.44%	6.22%	99.11%
Wavetronix Advance	SB21	0.00%	0.44%	2.67%	1.78%	96.44%
Aldis Upstream	SB38	7.57%	74.20%	1.93%	19.58%	65.53%
Aldis Stop Line	SB46	9.59%	1.84%	4.07%	2.44%	90.68%
Pod 100 ft from stop line	SB51	1.47%	0.37%	2.45%	0.18%	95.59%
Pod 200 ft from stop line	SB52	1.72%	0.43%	2.15%	0.18%	95.59%
Pod 300 ft from stop line	SB53	1.35%	0.67%	2.45%	0.12%	95.46%
Pod 400 ft from stop line	SB54	1.59%	0.80%	2.33%	0.18%	95.10%
Pod 500 ft from stop line	SB55	1.53%	1.53%	2.02%	0.25%	94.67%
Pod 600 ft from stop line	SB56	1.59%	2.39%	3.13%	0.25%	92.58%
Pod 700 ft from stop line	SB57	1.47%	2.33%	2.02%	0.06%	94.05%
Pod 800 ft from stop line	SB58	2.08%	4.05%	1.47%	0.00%	92.34%
Pod at stop line	SB59	1.66%	0.12%	2.27%	0.18%	95.77%
	Total	3.80%	6.80%	2.58%	2.35%	92.28%

Table 73. Summary Counts and Percents for Motorcycles.

Detector	Channel	No. Runs	Count		Percent	
			Miss	Not Miss	Miss	Not Miss
FLIR VIP Stop Line	SB5	53	2	51	3.77%	96.23%
Iteris Stop Line	SB13	28	0	28	0.00%	100.00%
Iteris Tripline at 485 ft	SB15	28	18	10	64.29%	35.71%
Wavetronix Matrix	SB17	25	0	25	0.00%	100.00%
Wavetronix Advance	SB21	25	0	25	0.00%	100.00%
Aldis Upstream	SB38	53	6	47	11.32%	88.68%
Aldis Stop Line	SB46	53	28	25	52.83%	47.17%
	Total	265	54	211	20.38%	79.62%

APPENDIX D. BOX PLOT DATA

Table 74. Box Plot Data Summary for 50 mph, Day, Dry.

Test Spd	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	SB5	366	-0.81	0.18	367	-0.27	0.09	0.54
50	SB13	222	-0.74	0.19	223	-0.07	0.26	0.67
50	SB15	191	2.73	0.15	189	6.27	0.69	3.54
50	SB17	75	-1.24	0.30	75	0.53	0.19	1.77
50	SB21	78	2.11	0.60	77	5.20	0.45	3.09
50	SB38	722	2.98	2.84	713	5.14	2.95	2.16
50	SB46	481	-1.42	1.19	481	0.43	1.17	1.84
50	SB51	466	0.97	0.09	466	1.39	0.07	0.41
50	SB52	464	2.36	0.12	464	2.77	0.08	0.41
50	SB53	465	3.74	0.13	465	4.16	0.11	0.41
50	SB54	465	5.12	0.15	465	5.53	0.14	0.41
50	SB55	465	6.51	0.17	465	6.91	0.16	0.40
50	SB56	463	7.88	0.20	463	8.29	0.19	0.41
50	SB57	464	9.26	0.22	464	9.66	0.22	0.41
50	SB58	459	10.64	0.25	451	11.05	0.25	0.41
50	SB59	467	-0.41	0.12	467	0.00	0.05	0.40

Table 75. Box Plot Data Summary for 70 mph, Day, Dry.

Test Spd	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
70	SB5	261	-0.77	0.18	263	-0.29	0.07	0.48
70	SB13	52	-0.66	0.16	53	-0.12	0.06	0.54
70	SB15	58	1.24	0.37	58	4.75	0.35	3.51
70	SB16	26	1.75	0.15	26	5.25	0.12	3.50
70	SB17	73	-1.12	0.16	73	0.17	0.20	1.29
70	SB21	79	1.97	0.24	79	4.98	0.54	3.00
70	SB38	227	1.65	1.31	225	3.67	1.79	2.02
70	SB46	361	-1.24	0.32	361	0.24	0.38	1.48
70	SB51	291	0.70	0.07	291	0.99	0.07	0.29
70	SB52	290	1.68	0.11	290	1.97	0.12	0.29
70	SB53	291	2.66	0.15	291	2.95	0.16	0.28
70	SB54	291	3.64	0.19	291	3.94	0.21	0.29
70	SB55	291	4.63	0.24	291	4.92	0.26	0.28
70	SB56	289	5.61	0.26	290	5.89	0.27	0.28
70	SB57	293	6.59	0.36	293	6.88	0.35	0.29
70	SB58	285	7.59	0.39	283	7.88	0.39	0.29
70	SB59	293	-0.29	0.05	293	0.00	0.00	0.29

Table 76. Box Plot Data Summary for 50 mph, Transition, Dry.

Test Spd	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	SB5	44	-0.75	0.08	44	-0.26	0.07	0.49
50	SB13	29	-0.71	0.07	29	-0.09	0.06	0.62
50	SB15	29	2.51	0.11	29	6.06	0.27	3.54
50	SB16							
50	SB17	45	-1.22	0.19	45	0.45	0.23	1.67
50	SB21	45	1.97	0.07	45	5.12	0.14	3.15
50	SB38	113	3.52	1.88	113	6.56	2.60	3.04
50	SB46	104	-1.42	0.57	105	0.54	0.46	1.96
50	SB51	118	0.98	0.05	118	1.36	0.06	0.38
50	SB52	119	2.36	0.07	119	2.72	0.08	0.37
50	SB53	120	3.72	0.09	120	4.10	0.10	0.38
50	SB54	120	5.09	0.11	120	5.46	0.11	0.37
50	SB55	119	6.45	0.13	119	6.83	0.13	0.38
50	SB56	120	7.82	0.16	120	8.19	0.17	0.37
50	SB57	119	9.19	0.19	119	9.56	0.19	0.37
50	SB58	119	10.55	0.21	119	10.84	1.03	0.29
50	SB59	118	-0.39	0.05	118	0.00	0.00	0.39

Table 77. Box Plot Data Summary for 70 mph, Transition, Dry.

Test Spd	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
70	SB5							
70	SB13	33	-0.59	0.06	33	-0.15	0.04	0.44
70	SB15	25	0.76	0.10	24	4.28	0.14	3.52
70	SB16	24	1.57	0.13	24	5.07	0.12	3.50
70	SB17							
70	SB21							
70	SB38	110	1.09	3.25	108	1.46	3.44	0.37
70	SB46	33	-1.00	0.08	33	0.33	0.07	1.33
70	SB51	33	0.69	0.05	33	0.99	0.05	0.30
70	SB52	33	1.65	0.05	33	1.95	0.07	0.30
70	SB53	33	2.63	0.05	33	2.91	0.07	0.28
70	SB54	32	3.60	0.07	32	3.91	0.08	0.31
70	SB55	31	4.57	0.10	31	4.86	0.10	0.29
70	SB56	33	5.54	0.10	33	5.83	0.11	0.28
70	SB57	32	6.49	0.11	32	6.77	0.12	0.28
70	SB58	32	7.49	0.14	32	7.76	0.13	0.28
70	SB59	33	-0.28	0.06	33	0.00	0.00	0.28

Table 78. Box Plot Data Summary for 50 mph, Night, Dry.

Test Spd	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	SB5	211	-0.74	0.49	212	-0.23	0.38	0.51
50	SB13							
50	SB15							
50	SB16							
50	SB17	40	-1.16	0.15	40	0.54	0.21	1.69
50	SB21	40	1.99	0.09	40	5.12	0.18	3.13
50	SB38	90	3.85	0.16	89	8.31	0.28	4.46
50	SB46	212	-1.10	0.71	213	0.87	0.14	1.97
50	SB51	213	1.00	0.05	213	1.37	0.06	0.37
50	SB52	213	2.38	0.07	213	2.72	0.08	0.34
50	SB53	213	3.74	0.10	213	4.09	0.11	0.35
50	SB54	213	5.10	0.12	213	5.45	0.14	0.35
50	SB55	213	6.47	0.14	213	6.81	0.17	0.35
50	SB56	213	7.83	0.18	213	8.18	0.20	0.36
50	SB57	212	9.19	0.21	211	9.54	0.23	0.35
50	SB58	210	10.55	0.24	210	10.91	0.26	0.36
50	SB59	212	-0.36	0.06	212	0.00	0.00	0.36

Table 79. Box Plot Data Summary for 70 mph, Night, Dry.

Test Spd	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
70	SB5	176	-0.72	0.60	178	-0.25	0.51	0.47
70	SB13							
70	SB15							
70	SB16							
70	SB17	70	-1.11	0.16	70	0.16	0.20	1.28
70	SB21	74	2.03	0.56	76	4.95	0.49	2.92
70	SB38	180	2.52	0.08	177	5.77	0.12	3.25
70	SB46	176	-1.12	0.08	176	0.40	0.08	1.52
70	SB51	175	0.68	0.05	176	0.97	0.05	0.29
70	SB52	179	1.65	0.06	179	1.93	0.06	0.28
70	SB53	180	2.63	0.07	180	2.90	0.06	0.28
70	SB54	179	3.59	0.08	179	3.88	0.07	0.29
70	SB55	179	4.57	0.09	179	4.86	0.09	0.29
70	SB56	177	5.54	0.10	177	5.83	0.10	0.29
70	SB57	180	6.51	0.12	180	6.79	0.11	0.29
70	SB58	179	7.48	0.13	179	7.78	0.13	0.29
70	SB59	176	-0.29	0.05	176	0.00	0.00	0.29

Table 80. Box Plot Data Summary for 50 mph, Day, Rain.

Test Spd	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
50	SB5	168	-1.00	0.59	169	-0.26	0.10	0.74
50	SB13	30	-0.77	0.10	31	-0.11	0.16	0.66
50	SB15	40	2.71	0.11	40	6.31	0.11	3.60
50	SB16							
50	SB17	31	-1.08	0.42	31	0.50	0.20	1.59
50	SB21	29	2.02	0.10	29	5.20	0.18	3.18
50	SB38	393	2.63	2.93	396	4.71	3.65	2.08
50	SB46	235	-1.37	0.93	233	0.68	0.51	2.05
50	SB51	231	0.96	0.11	231	1.37	0.07	0.42
50	SB52	232	2.34	0.10	232	2.74	0.09	0.40
50	SB53	232	3.71	0.11	232	4.11	0.11	0.40
50	SB54	230	5.07	0.14	230	5.48	0.14	0.41
50	SB55	232	6.44	0.16	232	6.85	0.16	0.40
50	SB56	232	7.81	0.18	232	8.22	0.18	0.41
50	SB57	232	9.18	0.21	232	9.57	0.21	0.40
50	SB58	232	10.54	0.23	231	10.94	0.23	0.40
50	SB59	232	-0.41	0.10	232	0.00	0.00	0.41

Table 81. Box Plot Data Summary for 70 mph, Day, Rain.

Test Spd	Channel	Off Sample	Off Mean	Off SD	On Sample	On Mean	On SD	Total On Time
70	SB5	65	-0.98	0.73	65	-0.28	0.20	0.70
70	SB13							
70	SB15	23	0.83	0.09	23	4.37	0.07	3.54
70	SB16	19	1.67	0.08	19	5.18	0.08	3.51
70	SB17	27	-1.05	0.12	27	0.21	0.24	1.26
70	SB21	30	1.98	0.11	30	5.14	0.15	3.16
70	SB38	75	1.48	1.47	76	3.22	1.47	1.74
70	SB46	68	-1.11	0.09	68	0.45	0.13	1.56
70	SB51	68	0.69	0.07	68	0.99	0.06	0.30
70	SB52	69	1.69	0.07	69	1.97	0.07	0.28
70	SB53	69	2.67	0.08	69	2.95	0.09	0.27
70	SB54	69	3.65	0.09	69	3.94	0.10	0.29
70	SB55	69	4.64	0.10	69	4.92	0.12	0.28
70	SB56	69	5.62	0.11	69	5.92	0.12	0.30
70	SB57	68	6.63	0.13	68	6.91	0.14	0.28
70	SB58	68	7.61	0.15	68	7.91	0.16	0.29
70	SB59	68	-0.29	0.07	68	0.00	0.00	0.29

APPENDIX E. GPS ACCURACY

INTRODUCTION

The analysis in this section is based on matching GPS records and Trafficware Pod detector event data. Both data were recorded on the same computer to ensure the same source of timestamps. Each Trafficware Pod was mapped to a specific channel in the controller. Pods were installed at 100-ft spacing from the stop line location (0 ft) to 800 ft upstream of the stop line. As a vehicle passes each Pod, the computer automatically records GPS traces and Pod on and off events. The timestamps of the detection events are used to locate the points within the GPS traces that can be used to identify specific locations of the vehicles at that moment. Based on these points, researchers used the GPS records to determine the precise locations of vehicles when each detection channel is activated and deactivated. Since the exact locations of the Pods are known, GPS accuracy can be verified as long as latency and other variables inherent in both systems are well enough understood. The GPS used in this project updates its position every 100 milliseconds so its location is predictable when mounted in a vehicle traveling in a straight line and at constant speed. The analysis examined the variability of the GPS-equipped vehicle locations at the detector events and the distance covered by the GPS during the on time of the Pods.

STUDY DESIGN

To investigate the accuracy of GPS, researchers used the matched GPS records at the on and off events of each Pod. For each vehicle run, the laptop computer recorded vehicle locations and corresponding timestamps at the on/off events. For the purpose of the analysis, researchers calculated the following measures from the data set:

- On Distance – The distance between the front bumper and the Pod location at the on detection event. This distance is positive if the vehicle's front bumper is approaching the Pod and negative if past the Pod. This value is zero if the Pod is activated when the front bumper just arrives at the Pod.
- Off Distance – The distance between the rear bumper and the Pod location at the off detection event. This distance is positive if the vehicle's rear bumper is approaching the Pod and negative if past the Pod. This value is zero if the Pod is deactivated when the rear bumper just passes the Pod.
- Presence Distance – The distance covered by the vehicle (based on GPS) when the Pod is on. The presence distance will equal the vehicle length if the Pod is activated and deactivated exactly when the front bumper reached the Pod and the rear bumper departs from the Pod.
- Extra Distance – This value is calculated by subtracting the vehicle length from the presence distance. The extra distance is positive is the presence distance is greater than the actual vehicle length and negative if less.

For each measure, researchers can determine if their observed values are influenced by specific factors such as lighting, weather, and Pod locations using a regression modeling technique. To ensure that the data used in this analysis are not affected by other factors such as human errors, the process applied the following filters to the dataset used in this analysis:

- On distance must be between10 ft and 45 ft.
- Off distance must be less than 5 ft.
- Presence distance must be between 4 and 45 ft.

With the filtering, the total number of observations used in the analysis dropped from 2,952 to 1,972 observations.

DESCRIPTIVE STATISTICS AND PLOTS

The research team computed the descriptive statistics to quantify the characteristics of GPS locations with respect to the known Pod locations at 100-ft spacings. Table 82 and Table 83 summarize the mean and standard deviation values for 50 mph and 70 mph test runs, respectively.

The On distance values are generally positive, which implies that the Pod is usually activated a few feet early before the front bumper arrives at the Pod. The Off distance values are mostly negative, which indicates that the Pod usually stays on for some distance after the rear bumper clears the Pod. The standard deviation is in the range of 5 to 10 ft indicating a range of variability expected with the GPS data with ping frequency at 10 Hz (every 100 milliseconds).

The Presence distance values are slightly longer than the vehicle length as indicated by mostly positive Extra Distance values. This finding is likely attributed mostly to late off detections by the Pods.

Two types of vehicles were used in the GPS runs. The length of Toyota Highlander is 15.5 ft, and the length of Dodge Caravan is 16.25 ft. Most of the GPS runs were carried out using the Highlander except for two days in February 2015 when the Dodge Caravan was used instead.

To illustrate the effects of approach speeds and lighting, Figure 70 through Figure 72 are box-and-whisker plots of On, Off, and Extra Distances with respect to each Pod location. The weather effect was also plotted but omitted herein due to the lack of any distinct patterns. In general, the trends are subtle and not easy to discern without the use of more rigorous statistical modeling techniques.

Table 82. Descriptive Statistics for 50 mph Runs.

Weather	Lighting	Pod Location (ft)	On Distance (ft)		Off Distance (ft)		Presence Distance (ft)		Extra Distance (ft)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Clear	Day	0	5.4	9.4	-8.9	5.5	14.3	8.6	-1.4	8.6
Clear	Day	100	5.3	9.0	-12.0	5.2	17.3	9.3	1.6	9.3
Clear	Day	200	6.7	8.9	-11.0	6.4	17.7	9.3	1.9	9.3
Clear	Day	300	6.7	9.4	-10.8	5.5	17.5	8.8	1.8	8.8
Clear	Day	400	6.7	9.2	-10.6	6.0	17.3	9.3	1.7	9.2
Clear	Day	500	4.8	8.3	-10.8	6.0	15.7	8.4	-0.1	8.3
Clear	Day	600	6.1	8.1	-10.5	5.5	16.7	8.7	0.9	8.6
Clear	Day	700	5.2	9.0	-10.9	5.6	16.1	9.6	0.4	9.6
Clear	Day	800	5.6	8.6	-9.9	5.7	15.4	7.5	-0.2	7.5
Clear	Night	0	7.7	6.7	-8.2	4.5	15.9	8.4	0.0	8.4
Clear	Night	100	2.9	5.5	-13.1	5.7	16.0	6.9	0.1	6.9
Clear	Night	200	5.1	10.8	-11.8	6.5	16.9	11.6	1.1	11.6
Clear	Night	300	6.6	9.1	-12.7	5.7	19.3	10.8	3.5	10.8
Clear	Night	400	3.7	9.8	-12.0	5.8	15.6	10.5	-0.2	10.6
Clear	Night	500	0.9	6.6	-11.5	4.5	12.4	7.7	-3.5	7.7
Clear	Night	600	4.8	9.0	-12.7	6.6	17.4	10.9	1.6	10.7
Clear	Night	700	6.7	10.5	-10.3	5.5	17.1	11.8	1.3	11.8
Clear	Night	800	5.4	9.8	-9.4	5.1	14.8	8.6	-0.8	8.6
Rain	Day	0	10.4	6.0	-6.7	4.6	17.1	5.0	1.6	5.0
Rain	Day	100	2.6	5.9	-13.2	4.9	15.8	5.7	0.3	5.7
Rain	Day	200	8.9	11.6	-9.6	3.1	18.5	11.7	3.0	11.7
Rain	Day	300	2.7	6.0	-9.9	4.9	12.6	5.6	-2.9	5.6
Rain	Day	400	2.3	6.4	-11.3	4.1	13.6	6.7	-1.9	6.7
Rain	Day	500	1.5	9.3	-10.9	5.1	12.4	8.9	-3.1	8.9
Rain	Day	600	1.7	4.5	-10.0	4.9	11.7	6.4	-3.8	6.4
Rain	Day	700	6.5	9.2	-6.8	4.5	13.3	8.6	-2.2	8.6
Rain	Day	800	9.5	8.5	-8.1	6.5	17.7	8.7	2.2	8.7

Table 83. Descriptive Statistics for 70 mph Runs.

Weather	Lighting	Pod Location (ft)	On Distance (ft)		Off Distance (ft)		Presence Distance (ft)		Extra Distance (ft)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Clear	Day	0	7.0	10.6	-9.3	6.0	16.3	9.2	0.8	9.2
Clear	Day	100	5.6	9.8	-12.7	8.2	18.3	10.4	2.8	10.4
Clear	Day	200	5.3	9.6	-13.3	6.4	18.6	10.2	3.1	10.2
Clear	Day	300	3.6	8.6	-14.4	6.4	17.9	8.9	2.4	8.9
Clear	Day	400	4.6	10.8	-12.4	6.7	17.0	11.1	1.5	11.1
Clear	Day	500	7.8	9.4	-12.8	7.4	20.7	10.8	5.2	10.8
Clear	Day	600	6.4	8.3	-13.0	6.9	19.4	10.6	3.9	10.6
Clear	Day	700	6.2	10.4	-12.3	6.7	18.5	10.9	3.0	10.9
Clear	Day	800	7.3	10.6	-12.1	7.7	19.4	10.2	3.9	10.2
Clear	Night	0	8.0	11.2	-10.1	5.2	18.1	11.7	1.9	11.6
Clear	Night	100	3.4	8.5	-15.3	8.0	18.7	12.5	2.6	12.4
Clear	Night	200	0.4	8.0	-18.1	7.2	18.5	11.8	2.4	11.8
Clear	Night	300	4.2	9.4	-13.1	6.4	17.3	9.3	1.1	9.4
Clear	Night	400	7.4	10.1	-16.9	8.1	24.3	11.7	8.2	11.7
Clear	Night	500	2.1	7.2	-15.0	6.9	17.1	9.2	1.0	9.3
Clear	Night	600	2.4	8.9	-16.9	5.7	19.3	10.1	3.2	10.1
Clear	Night	700	6.4	11.3	-14.5	7.7	20.9	12.6	4.7	12.5
Clear	Night	800	3.4	8.8	-15.9	8.8	19.3	11.1	3.2	11.1
Rain	Day	0	7.9	10.1	-9.4	5.0	17.3	8.6	1.8	8.6
Rain	Day	100	9.3	9.0	-13.6	8.6	22.9	13.2	7.4	13.2
Rain	Day	200	4.4	11.2	-14.8	8.4	19.3	9.0	3.8	9.0
Rain	Day	300	4.7	9.7	-13.7	8.5	18.5	10.2	3.0	10.2
Rain	Day	400	4.4	9.1	-15.0	8.2	19.5	10.5	4.0	10.5
Rain	Day	500	4.8	12.2	-9.0	8.4	13.7	9.0	-1.8	9.0
Rain	Day	600	5.3	6.5	-15.1	4.8	20.4	7.0	4.9	7.0
Rain	Day	700	3.7	9.0	-13.2	8.1	17.0	11.3	1.5	11.3
Rain	Day	800	6.6	7.5	-13.1	8.3	19.7	10.0	4.2	10.0

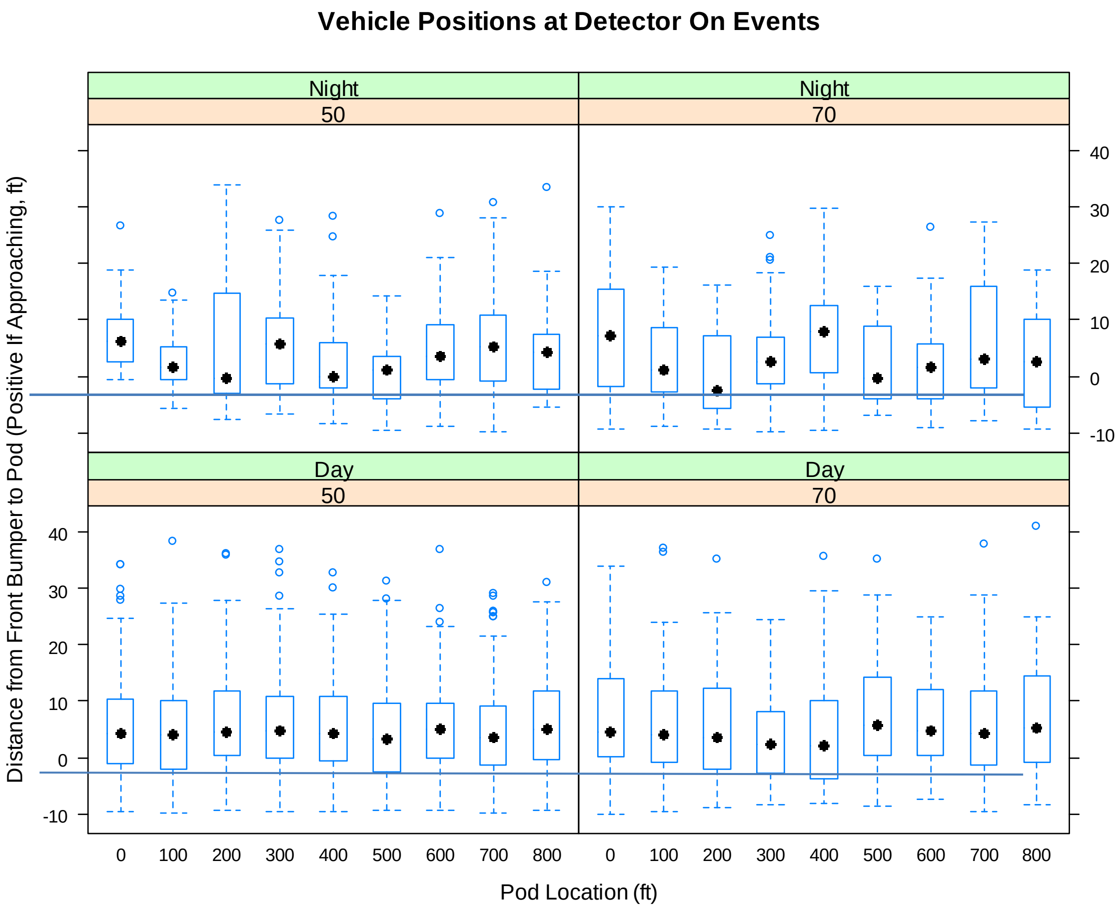


Figure 70. Box Plots of On Distances.

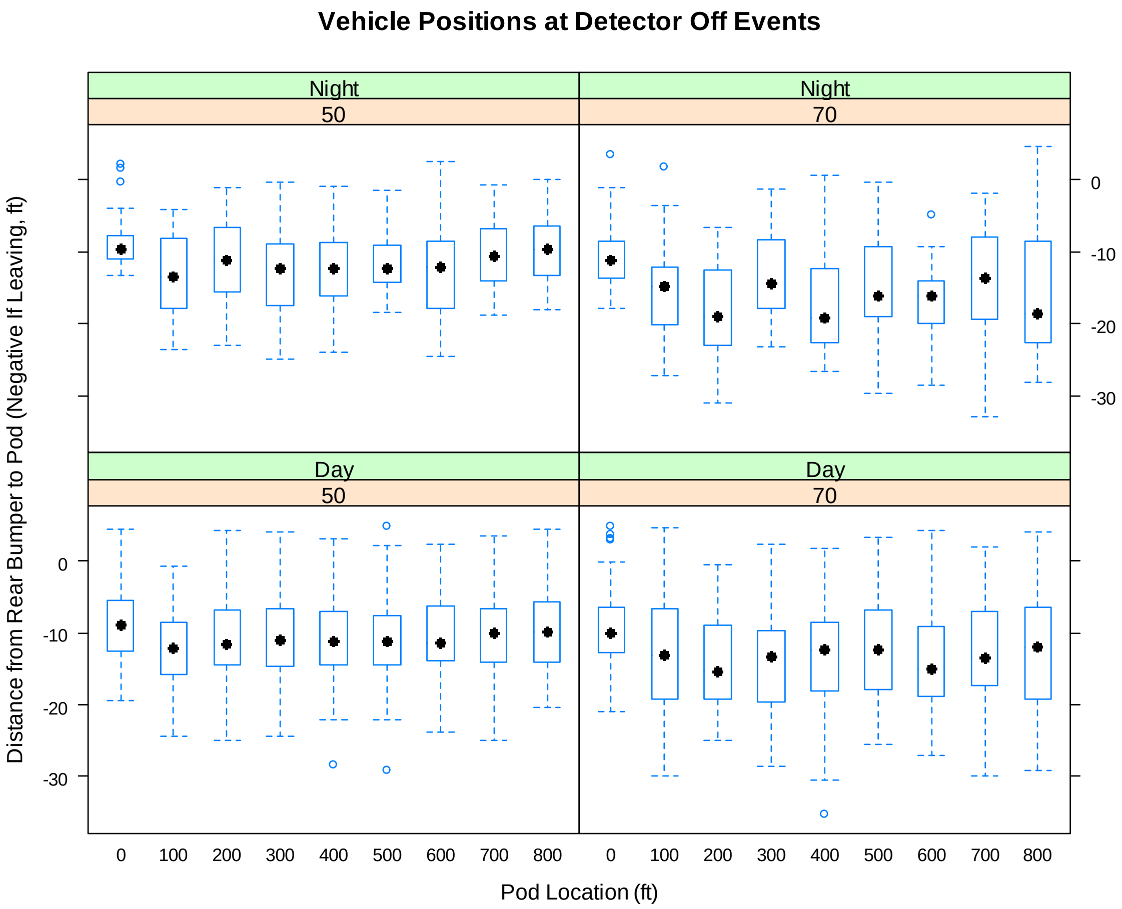


Figure 71. Box Plots of Off Distances.

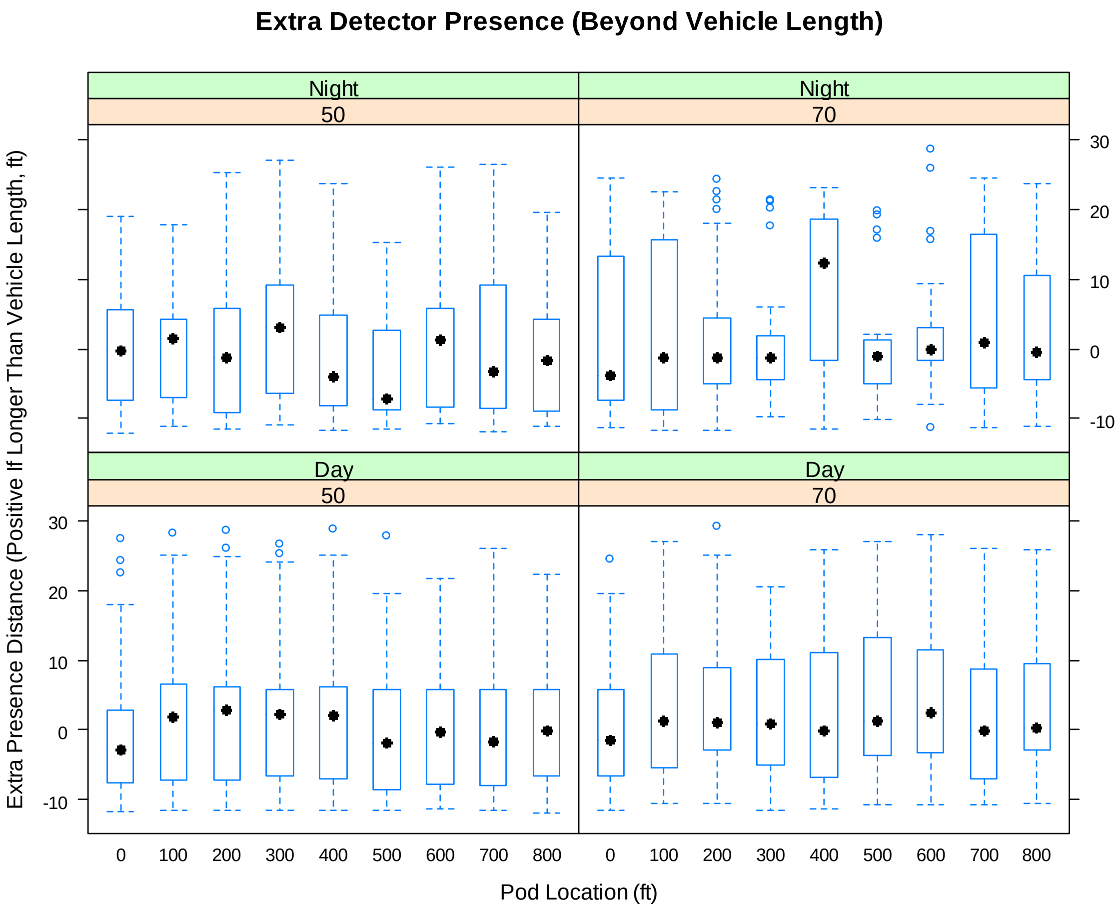


Figure 72. Box Plots of Extra Distances.

Regression Models

The research team used a linear regression model to examine the effects of weather, lighting, and Pod location on the detection distances at the on and off events. Three models calibrated are for (a) On Distance, (b) Off Distance, and (c) Extra Distance.

On Distance

The On Distance model pertains to the relative location of GPS vehicles when the detector is activated. The modeling results show that the weather, lighting, and pod locations have no statistically significant impacts on the On Distance. Table 84 shows the final model for the On Distance. Note that this is an intercept-only model because no factors are shown to have significant influences on the response variable. The coefficient estimate indicates that the Pod on average came on 5.6 ft before the front bumper arrives at the Pod. This standard deviation of the average on distance is 0.2 ft.

Table 84. On Distance Regression Results.

Coefficients	Estimate	Std. Error	t value	p-value
(Intercept)	5.5681	0.2059	27.05	<2e-16

Residual standard error: 9.142 on 1971 degrees of freedom

Off Distance

Table 85 shows the Off Distance regression modeling results. The weather (clear versus rainy) does not have any impact on the off detection. However, the lighting, approach speed, and the stop line Pod locations were found to have statistically significant effects on the vehicle location when the Pod is deactivated.

Under daytime testing at 50 mph, the Pod went off when the rear bumper was about 10.7 ft past the Pod. The corresponding standard deviation is 0.2 ft. The higher approach speed of 70 mph was found to increase this distance by another 2.5 ft. This is likely due to the decrease in the positional accuracy of GPS at the higher speed. The Pod at the stop line location was found to have the earliest off distance, i.e., 3.0 ft earlier than other Pod locations upstream. It is possible that drivers began decelerating too soon after reaching the stop line for some of the test runs, thus contributing to the early off distance compared to other Pod locations. In fact, a closer examination of the box plots in Figure 71 will show that the box plots at 0 ft (stop line location) are slightly higher than those at other Pod locations in most cases. This finding is consistent with the regression results. Under nighttime test conditions, the off distance increased by 1.6 ft compared to daytime. It is unclear what could have contributed to this difference for nighttime testing.

Table 85. Off Distance Regression Results.

Coefficients	Estimate	Std. Error	t value	p-value
(Intercept)	-10.7124	0.1918	-55.867	< 2e-16
Night	-1.6084	0.3522	-4.567	5.25E-06
70 mph Spd	-2.4677	0.2936	-8.405	< 2e-16
Stop Bar Location	3.0328	0.4523	6.706	2.61E-11

Residual standard error: 6.234 on 1968 degrees of freedom

Multiple R-squared: 0.06943, Adjusted R-squared: 0.06801

F-statistic: 48.94 on 3 and 1968 DF, p-value: < 2.2e-16

The average on distance of 5.6 ft and the average off distance of 10.7 ft add up to 16.3 ft, which is about the length of the test vehicle.

Extra Distance

The extra distance is modeled instead of the presence distance because it is unaffected by the length of the vehicle. The extra distance is the distance beyond the vehicle length covered by the GPS when the Pod is present. Ideally, the value should be zero but due to sensitivity of the Pods and the GPS characteristics it can be either positive or negative. The positive value signifies that the GPS covered a distance longer than the length of the vehicle and the opposite for a negative value. Table 86 summarizes the regression results of the extra distance.

Only the approach speed was found to have a statistically significant effect on the extra distance. In general, the extra distance is about 0.6 ft for 50 mph runs. The extra distance is observed to increase by 2.5 ft for 70 mph runs. The weather, lighting, and Pod locations did not have any impacts on the extra distance.

Table 86. Extra Distance Regression Results.

Coefficients	Estimate	Std. Error	t value	p-value
(Intercept)	0.5608	0.2695	2.081	0.0375
70 mph Spd	2.5395	0.445	5.707	1.33E-08

Residual standard error: 9.523 on 1970 degrees of freedom

Multiple R-squared: 0.01626, Adjusted R-squared: 0.01576

F-statistic: 32.57 on 1 and 1970 DF, p-value: 1.327e-08

Conclusions

The analysis of GPS versus Pod detection data shows that significant discrepancies exist between the two methods of calculating vehicle speed and position. After careful examination of both results, the research team decided to use the detector data originating with Pod detections and to use the GPS results only as supportive information where appropriate. GPS can provide adequate support where only presence detections are needed but not for position information. Besides, GPS data were only available for one vehicle whereas the other dataset had all vehicles.

REFERENCES

1 Bonneson, J., S. Sunkari, M. Pratt, and P. Songchitruksa. *Traffic Signal Operations Handbook, Second Edition*. Report No. FHWA/TX-11/0-6402-P1. Texas Transportation Institute, College Station, Texas, October 2011.

2 Zimmerman, K., J. Bonneson, M. Pratt, and S. Sunkari. *Technical Memorandum No. 2: Summary of Signal Timing Interviews with District Traffic Personnel.* TxDOT Project 0-5629. Texas Transportation Institute, the Texas A&M University System, College Station, Texas, June 2007.

3 Sun, D., L. Dodoo, A. Rubio, H.K. Penumala, M. Pratt, and S. Sunkari. *Synthesis Study of Texas Signal Control Systems: Technical Report*. Report No. FHWA/TX-13/0-6670-1. Texas A&M University-Kingsville, Kingsville, Texas, November 2012.

4 Bonneson, J., D. Middleton, K. Zimmerman, H. Charara, and M. Abbas. *Intelligent Detection-Control System for Rural Signalized Intersections.* Technical Report FHWA/TX-03/4022-2, Texas Transportation Institute, August 2002.

5 Urbanik, T., and P. Koonce. "The Dilemma with Dilemma Zones." http://redlightrobber.com/red/links_pdf/The-Dilemma-with-Dilemma-Zones.pdf, Accessed September 8, 2014.

6 U.S. Department of Transportation. "Intelligent Transportation Systems Deployment Statistics." http://www.itsdeployment.its.dot.gov/default.asp, Accessed November 1, 2006.

7 Li, Z., H. Wei, Z. Yao, H. Xiong, and X. Yan. "Optimized Advance Detector Configuration for Option Zone Protection at High-Speed Signalized Intersections." *Transportation Research Record: Journal of the Transportation Research Board*, No. 2355, 2013, pp. 60–72.

8 Zegeer, C. V. "Effectiveness of Green-Extension Systems at High-Speed Intersections." *Research Report 472*, Bureau of Highways, Kentucky Department of Transportation, Lexington, 1977.

9 Sharma, A., D. M. Bullock, and S. Peeta. "Recasting Dilemma Zone Design as a Marginal Cost-Benefit Problem." *Transportation Research Record: Journal of the Transportation Research Board*, No. 2035, 2007, pp. 88–96.

10 Bonneson, J. A., P. T. McCoy, and B. A. Moen. *Traffic Detector Design and Evaluation Guidelines*. Report TRP-02-31-93, Nebraska Department of Transportation, Lincoln, 1994.

11 Bonneson, J. A., and P. T. McCoy. *Manual of Traffic Detector Design*, 2nd Edition. May 2005.

12 Gates, T. J., and D. A. Noyce. “Dilemma Zone Driver Behavior as a Function of Vehicle Type, Time of Day, and Platooning.” *Transportation Research Record: Journal of the Transportation Research Board*, No. 2149, 2010, pp. 84–93.

13 Bonneson, J., S. Sunkari, and M. Pratt. *Traffic Signal Operations Handbook*. Report FHWA/TX-09/0-5629-P1, Texas Transportation Institute, College Station, TX, March 2009.

14 Sharma, A., D. M. Bullock, and S. Peeta. “Limitations of Simultaneous Gap-Out Logic.” *Transportation Research Record: Journal of the Transportation Research Board*, No. 1978, 2006, pp. 42–48.

15 Middleton, D. R., D. Jasek, H. Charara, and D. Morris. *Evaluation of Innovative Methods to Reduce Stops to Trucks at Isolated Signalized Intersections.* Report No. TX-97/2972-S, Texas Transportation Institute, September 1997.

16 Peterson, A., T. Bergh, and K. Steen. “LHOVRA: A New Traffic Signal Control Strategy for Isolated Junctions.” *Traffic Engineering and Control*, Vol. 27, No. 7/8, 1986, pp. 388–389.

17 Kronborg, P., F. Davidson, and J. Edholm. *SOS - Self Optimising Signal Control: Development and Field Trials of the SOS Algorithm for Self-Optimising Signal Control at Isolated Intersections.* Report 1997:2E, TFK (Transport Research Institute), Stockholm, Sweden, 1997.

18 Smaglik, E. J., D. M. Bullock, T. Urbanik, and D. Bryant. “Evaluation of Flow-Based Traffic Signal Control Using Advanced Detection Concepts.” *Transportation Research Record: Journal of the Transportation Research Board*, No. 1978, 2006, pp. 25–33.

19 Pratt, M. P., and J. A. Bonneson. “Framework for Evaluating Advance-Detection Designs for High-Speed Intersection Approaches.” *Transportation Research Record: Journal of the Transportation Research Board*, No. 2192, 2010, pp. 127–135.

20 Aldis. “Here Are a Few Reasons Why You’ll Love GridSmart®,” http://www.aldiscorp.com/gridsmart/, Accessed September 15, 2014.

21 FLIR. “Thermal Sensors for Traffic Applications,” http://www.flir.com/cvs/americas/en/traffic/view/?id=62099, Accessed September 9, 2014.

22 Sensys Networks. “FlexMag.” http://www.sensysnetworks.com/products/sensor/, Accessed September 15, 2014.

23 Trafficware. “Valence Pod System,” http://www.trafficware.com/wp-content/uploads/2013/08/Valence-Pod-System-Brochure_05-23-2013.pdf, Accessed September 15, 2014.

24 Wavetronix, LLC, “SmartSensor Matrix.” http://www.wavetronix.com/en/products/smartsensor/matrix/features , accessed September 6, 2014.

25 Iteris. “Vantage Vector Hybrid,” http://www.iteris.com/products/cameras/vantage-vector-hybrid, Accessed September 7, 2014.

26 FLIR. “TrafiRadar,” http://www.flir.com/uploadedFiles/CVS_Americas/Traffic/Products/TrafiRadar/FLIR-TrafiRadar-Datasheet.pdf, Accessed September 14, 2014.

27 MS Sedco. Intersector™ Microwave Motion and Presence Sensor, http://www.mssedco.com/pdf/pdfmanuals/ck1-im.pdf, Accessed September 15, 2014.

28 Wavetronix. “SmartSensor Advance,” http://www.wavetronix.com/en/products/smartsensor/advance/features, Accessed September 14, 2014.

29 Lee, D. “Revolutionizing Signal Control with Thermal Traffic Detection Cameras” *IMSA Journal*, Vol. L, Issue 2, pp. 42–43, 2012.

30 Grossman, J., A. Hainen, S. Remias, and D. Bullock. “Evaluation of Thermal Image Video Sensors for Stop Bar Detection at Signalized Intersections,” *Transportation Research Record: Journal of the Transportation Research Board,* No. 2308, pp.184–198, Washington, D.C., 2012.

31 Springer Link. “Vehicle Detection Even in Poor Visibility Conditions Using Infrared Thermal Images and Its Application to Road Traffic Flow Monitoring,” http://link.springer.com/chapter/10.1007/978-1-4614-3558-7_85, Accessed September 2, 2014.

32 Iwasaki, Y., M. Masato, and T. Nakamiva. *Robust Vehicle Detection under Various Environmental Conditions Using an Infrared Thermal Camera and its Application to Road Traffic Flow Monitoring.* Department of Information Engineering, Graduate School of Industrial Engineering, Tokai University, Kumamoto, Japan, April 2013.

33 Wavetronix. “Counting Vehicles on Signalized Roadways Using the SmartSensor Matrix,” http://www.wavetronix.com/uploads/download/file/309/an0013_-_counting_vehicles_on_signalized_roadways_using_the_smartsensor_matrix-20111215113210.en.pdf, Accessed September 14, 2014.

34 Middleton, D., H. Charara, and R. Longmire. *Alternative Vehicle Detection Technologies for Traffic Signal Systems: Technical Report*. Report No. FHWA/TX-09/0-5845-1, Texas A&M Transportation Institute, The Texas A&M University System, College Station, TX, February 2009.

35 Medina, J.C., R.F. Benekohal, and A. Hajbabaie. *Evaluation of Sensys Wireless Vehicle Detection System: Results from Adverse Weather Conditions*. Report No. FHWA-ICT-11-081. Illinois Center for Transportation, University of Illinois at Urbana-Champaign, Urbana, Illinois, March 2011.

36 Medina, J.C., R.F. Benekohal, and H. Ramezani. *Field Evaluation of Smart Sensor Vehicle Detectors at Intersections – Volume 1: Normal Weather Conditions*. Report No. FHWA-ICT-12-016. Illinois Center for Transportation, University of Illinois at Urbana-Champaign, Urbana, Illinois, October 2012.

37 Medina, J.C., R.F. Benekohal, and H. Ramezani. *Field Evaluation of Smart Sensor Vehicle Detectors at Intersections – Volume 2: Performance Under Adverse Weather Conditions*. Report No. FHWA-ICT-13-014. Illinois Center for Transportation, University of Illinois at Urbana-Champaign, Urbana, Illinois, April 2013.

38 Medina, J.C., M. Chitturi, and R.F. Benekohal. Effects of Fog, Snow, and Rain on Video Detection Systems at Intersections. *Transportation Letters: The International Journal of Transportation Research*, Vol. 2, 2010, pp. 1–12.

39 Iwasaki, Y., S. Kawata, and T. Nakamiya. “Vehicle Detection Even in Poor Visibility Conditions Using Infrared Thermal Images and Its Application to Road Traffic Flow Monitoring.” *Emerging Trends in Computing, Informatics, Systems Sciences, and Engineering*. Springer Science + Business Media, New York, 2013.

40 Iwasaki, Y., M. Misumi, and T. Nakamiya. “Robust Vehicle Detection under Various Environmental Conditions Using an Infrared Thermal Camera and Its Application to Road Traffic Flow Monitoring.” *Sensors*, Vol. 13, 2013, pp. 7756–7773.

41 Chitturi, M.V., J.C. Medina, and R.F. Benekohal. “Effect of Shadows and Time of Day on Performance of Video Detection Systems at Signalized Intersections.” *Transportation Research Part C*, Vol. 18, 2010, pp. 176–186.

42 Sharma, A., M. Harding, B. Giles, D. Bullock, J. Sturdevant, and S. Peeta. “Performance Requirements and Evaluation Procedures for Advance Wide Area Detectors,” Paper presented at the 2008 TRB Annual Meeting, Washington, D.C. 2008.

43 Chitturi, M., J. C. Medina, and R. F. Benekohal. “Testbed for Evaluation of Vehicular Detection Systems.” *Journal of Advanced Transportation*, Vol. 44, No. 3, 2010, pp. 123–133.

44 Hurwitz, D. S., M. A. Knodler, Jr., H. Tuss, J. Swake, and D. Moore. “Evaluation of Effects Associated with Advanced Vehicle Detection Systems on Dilemma-Zone Protection.” Presented at 91st Annual Meeting of the Transportation Research Board, Washington, D.C., 2012.

45 Middleton, D., R. Longmire, H. Charara, D. Bullock, and J. Bonneson. *Improving Stop Line Detection Using Video Imaging Detectors*, Report No. FHWA/TX-10/0-6030-1, Texas A&M Transportation Institute, The Texas A&M University System, College Station, TX, March 2010.

46 Dalgleish, D. “Create a Simple Box Plot in Excel.” Contextures Blog. June 11, 2013. http://blog.contextures.com/archives/2013/06/11/create-a-simple-box-plot-in-excel/ , Accessed September 10, 2015.