IMPROVING ADAPTIVE/RESPONSIVE SIGNAL CONTROL PERFORMANCE: IMPLICATIONS OF NON-INVASIVE DETECTION AND LEGACY TIMING PRACTICES

Final Report

SPR 781

RESEARCH

Oregon Department of Transportation

IMPROVING ADAPTIVE/RESPONSIVE SIGNAL CONTROL PERFORMANCE: IMPLICATIONS OF NON-INVASIVE DETECTION AND LEGACY TIMING PRACTICES

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16. Abstract: This project collected and analyzed event based vehicle detection data from multiple technologies at four different sites across Oregon to provide guidance for deployment of non-invasive detection for use in adaptive control, as well as develop a true life cycle cost comparison of various detection sources. Data during fair weather from non-invasive detection zones co-located with inductive loops were compared under based upon typical metrics used for driving adaptive algorithms, such as activations, occupancy, and time to gap out. From this analysis, it was recommended that non-invasive detection sources should be used with caution for developing data for adaptive control, as the inherent nature of their operation differs from inductive loops. From a life cycle cost standpoint, non-invasive units were shown to be much more expensive than inductive detection over the typical lifespan, but modest efficiency and safety improvements possible due to expanded features of the non-invasive units may overcome this cost deficit. Lastly, due to performance issues encountered with over 50% of the inductive loop detectors within this study, it is highly recommended to implement some type of continual detector health monitoring program regardless of technology selected for deployment.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

ODOT is turning towards adaptive/responsive signal control strategies to improve the operational performance of coordinated corridors and networks. However, these newer control strategies require more information from detection systems than traditional control strategies. This requirement for higher resolution detection data could be addressed through the selection of in pavement detection. However, due to the perceived capital costs associated with in-pavement detection systems, ODOT has increasingly been selecting non-invasive or passive detection systems such as video cameras, micro-wave, radar, or micro detection pucks, which are purported to be easier to install and maintain.

It is believed that these non-invasive systems are currently performing below those standards established by the use of in-pavement detection. As such, ODOT is currently operating adaptive and responsive signal control by applying legacy timing and installation practices, and in doing so is not maximizing the benefits of its investment in advanced control strategies.

Current ODOT standards of practice for purchase, installation, layout and timing of non-invasive systems requires updating. More realistic costs and guidance is needed in order to capture the full measure of the more powerful data intensive traffic signal controller systems currently being deployed throughout the State of Oregon.

This research will provide guidance for the selection of detection technologies for deployment based upon data driven analyses of various metrics used to drive adaptive as well as legacy timing control. Additionally, a life cycle cost analysis of various detection and control technologies will provide perspective for determining the true installation and operational costs of these devices.

Chapter 2.0 presents the findings of a comprehensive literature review of vehicle detection performance in relation to control and life cycle cost analyses related to adaptive control, as well as the results of a practitioner survey that investigated policies related to poor detection performance. This chapter concludes with a description of the overall methodology employed in this work.

Chapter 3.0 discusses the process that was carried out to select sites for data collection for this work. Using specific criteria, four sites were selected, and the details of the detection and control at these sites is documented.

Chapter 4.0 presents the details of the data collection process carried out in this work. The development of software and hardware modules created specifically for this project is discussed, as well as the methods that were used to collect the event based data from the individual sites.

In Chapter 5.0, the process used to compile and verify data used for modeling is explained. Given that the modeling is based upon inductive loop outputs, the operation of each sensor was verified to identify the loops with reliable operation. In addition, collected data was filtered to ensure a data set based upon ‘normal’ conditions (no rain and good visibility).

Chapter 6.0 presents the analysis of advance sensor operation. The performance of advance detection zones is analyzed for three separate metrics: number of activations, occupancy, and time to gap out. Data is analyzed through qualitative and quantitative methods to develop overarching guidance for advance detection zones.

Chapter 7.0 analyzes the performance of detection zones at the stop bar for three separate metrics: time to gap out, time to first sustained call, and split failure identification. Similar to Chapter 6.0, these metrics are also analyzed with qualitative and qualitative methods to develop additional guidance for detection deployment, but for stop bar sensors.

In Chapter 8.0, the results of a Life Cycle Cost Analysis for various detection and control technologies is presented. This chapter begins with an explanation of how various costs were developed for the analysis, and the presents the results of a number of analyses of various devices over different life cycle durations.

Chapter 9.0 ties together all of the recommendations and guidance developed in the previous chapters of the work, and presents recommendations for deployment of non-invasive detection in an adaptive control environment. Finally, suggestions for future work are presented.

2.0 LITERATURE REVIEW AND METHODOLOGY

The objective of this literature review is to explore previous research in areas relevant to this work, specifically in the areas of vehicle detector performance as it relates to intersection control as well as life cycle cost analyses relating to detection and adaptive control.

2.1 DETECTION PERFORMANCE IN RELATION TO CONTROL

Outside of downtown grid networks, signalized intersections are typically operated with some type of actuation. The complexity of the actuated control algorithm is directly related to the vehicle detection required to effectively operate the control. With control algorithms ranging from legacy call and extend operation to complex traffic responsive and adaptive operations, detection requirement can vary from as simple as a presence detection zone to call a side street phase for service to an array of sensors covering a network tasked with delivering presence, count, occupancy, and other metrics to an adaptive system.

Vehicle detection falls into two general categories, invasive technologies, those which are within the pavement, and non-invasive technologies, located outside of the roadway surface. Invasive sensors are commonly based upon inductive detection, taking the form of an in-pavement wire loop, preformed loop, small form factor loop (micro-loop), or wireless magnetometer. Non-invasive sensors vary in technology, including video, both visible and infrared, radar, and recently to the market, combination video and radar units. Each technology, be it invasive or non-invasive, comes with own unique benefits and challenges. In-pavement wired loops have been deployed in vehicle sensing operations for fifty years, with wireless magnetometer units entering the marketplace a little less than a decade ago. Various non-invasive sources have been employed in assorted vehicle detection operations for more than twenty plus years. Given the rate at which technology moves, literature documented in this review for the investigation of the link between detection performance and control will be limited to that published within the last ten years, unless the document is critical to the comparison, as all literature has been examined. Lastly, this review will focus on performance at signalized intersections (as opposed to free flow facilities).

2.1.1 Invasive Detection

2.1.1.1 Inductive Loops

Inductive detection is the most widely used sensor for vehicle detection *(Day et al. 2009)* and, when functioning properly, have long been purported to be the most accurate detection technology available. The Indiana Department of Transportation (INDOT) developed a detection performance specification *(Indiana Department of Transportation 2008, Middleton et al. 2009)* to address the issue of detector latency and other performance issues. To date, only invasive inductive technologies have satisfied the specification *(Sturdevant, INDOT; unpublished data)*. For reference, Oregon does not have a hard standard such as this. In addition, inductive loop detection has been used as a ground truth basis in a number of other detection performance evaluations *(Day et al. 2007, Rhodes et al. 2006, Grossman et al. 2012, Rhodes et al. 2007)*. Inductive loops are not without their challenges, however. Placing loops directly into the pavement can exacerbate pavement distress. While preformed loops placed under the surface course do not have this drawback, both types of installations are susceptible being compromised due to common in-ground hazards, including freeze/thaw cycling, vermin, and wayward construction equipment.

Recent technical operational research in the area of inductive loop detection has been limited, as the sensing technology is fairly mature. One document investigated the sensitivity of different loop configurations in three dimensions *(Day et al. 2009)* finding historical claims that quadrapole loops were more sensitive than rectangular loops to be unsubstantiated. In the area of counting at signalized intersections, long inductive loops (> 6') have been shown to count fairly accurately, within 10% of actual, when an amplifier with a count algorithm is used *(Smaglik et al. 2007)* There has been much work focusing on additional algorithmic uses of inductive loop outputs including the identification of malfunctioning loops through output analysis*(Wall and Dailey 2003; Weijermars and Van Berkum 2006)* however this hasn't been linked to higher level traffic control inputs.

2.1.1.2 Magnetometers

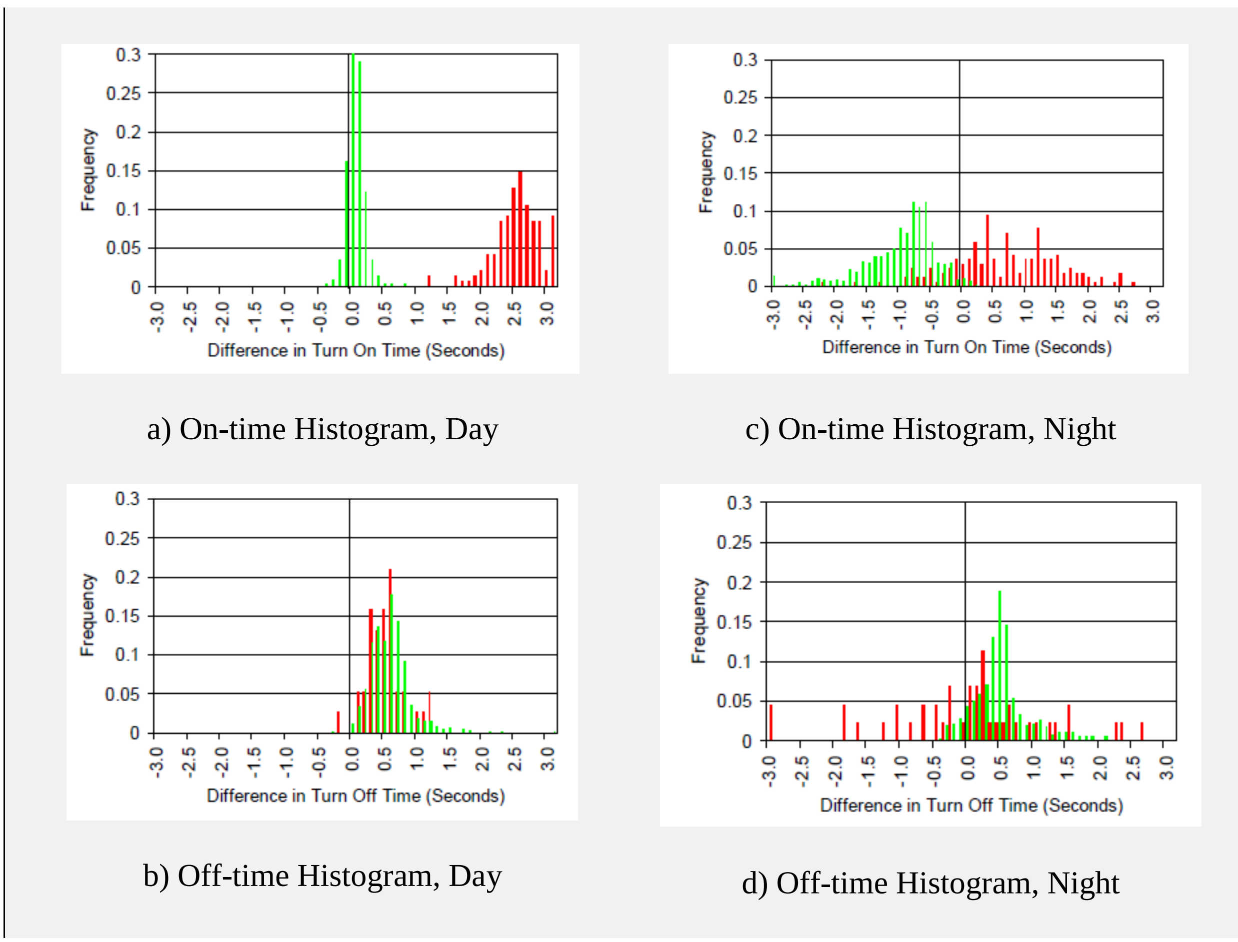
Magnetometers, either wired or wireless, operate similarly to inductive loops, but with a much smaller footprint. In one study, under urban traffic conditions wired magnetometers were shown to produce volume and speed counts on par with loops, although the author noted a potential for double counting due to vehicle lane changes *(Minge et al. 2010*. Another study undertaken by the Texas Transportation Institute (TTI) noted that wired magnetometers over counted vehicles 5-7% *(Middleton et al. 2008)*, and missed one motorcycle during the test. The researchers did not feel that the overcounting would be an issue for presence detection, but did express concern about the missed motorcycle.

Studies focused on wireless magnetometers showed similar performance to that of the wired magnetometer *(Haoui et al. 2008)*, with one study reporting over counting of 3-8% *(Middleton et al. 2008)*. The authors attributed this to lapses in communication with the wireless technology. Regarding presence detection, another study found that wireless magnetometers performed similar to loop detectors in terms of missed calls, with a slightly higher tendency to place a false call *(Day et al. 2007)*. No studies were found that directly linked magnetometer performance to advanced intersection control.

2.1.2 Non-Invasive Detection

2.1.2.1 Video Detection: Visible Spectrum

Video detection originated in the late 1970s and saw its first commercial installations in the early 1990s. The vast majority of video detection systems use a technique called "background subtraction," wherein the software isolates the background of the image from the vehicles and then places calls to the traffic controller when vehicles are detected in user-placed zones. The performance of those systems discussed here use background subtraction. Prior to development of their performance specification *(Indiana Department of Transportation 2008)*, researchers at Purdue University did the first evaluation of video detection performance in relation to inductive loop detectors. In one study, following manufacturer recommended mounting locations of 40' high on the far mast-arm located transversely between the through and left turn movements, the video detection units produced statistically significantly more false and missed calls than the inductive loops *(Rhodes et al. 2006)*. This work also investigated the difference in activation / deactivation times of the video unit compared to the inductive loop. Figure 2.1 shows four separate histograms from this report comparing the on- and off-times of the inductive loop against the video detector. In these histograms, the zero point represents the point in time when the loop turned on or off, depending on the histogram. Left of the zero point means the video unit activated / deactivated prior to the loop; right of the zero point means the video unit activated / deactivated after the loop. Bars in red represent activations / deactivations during the red phase for the movement. Bars in green represent activations / deactivations during the green phase for the movement. Of interest in these plots is that the latency of the video unit varies day and night as well as during red and green.



a) On-time Histogram, Day

c) On-time Histogram, Night

b) Off-time Histogram, Day

d) Off-time Histogram, Night

Figure 2.1: Video detection histograms *(Rhodes et al. 2006)*

Another study compared cameras from three separate vendors against loop detectors and saw similar results as the previous study regarding false and missed calls *(Rhodes et al. 2007)*, but also did an additional analysis of the units 5 months after the original work without reconfiguring the units. This additional analysis found that the performance of each unit degraded over time, implying that units might need to be reconfigured after that short period.

Researchers at the University of Champaign-Urbana have conducted a number or studies on the performance of video units *(Medina et al. 2008, Medina et al. 2009a, Medina et al. 2009b)*, and found the following:

- Configuration changes
  - The vendor of each camera was given feedback after seven weeks of operation of his originally set-up system and was thereafter allowed to adjust his system's configuration.
  - The configuration modifications generally improved operation of one measure to the detriment of another, e.g., a decrease of missed calls at the expense of an increase in false calls.
- Differing lighting conditions
  - The systems' operation was observed under different lighting conditions (cloudy, sunny, etc.), and the following observations were made:
    - The best performance was observed at mid-day during cloudy weather.
    - On sunny mornings, false calls increased on approaches with shadows perpendicular to that approach. Similar increases were observed at dusk.
    - Increases in false and missed calls were observed as light conditions deteriorated from the ideal.
- Changing weather conditions
  - The operation of the systems was observed under different weather conditions (fog, rain, snow, etc.) and the following observations were made:
    - During a dense fog, two of the three systems went into recall, while the third increased its number of false calls.
    - Snow greatly increased false calls.
    - Rain without wind also increased false calls.

Several works have provided insight on how to properly mount video detection units to mitigate issues identified previously *(Rhodes et al. 2007, Middleton et al. 2010, Tian and*

Abbas 2007), and TTI put together a short list of maintenance needs for video detection *(Middleton et al. 2010)*. The maintenance suggested to be performed every 6 months were:

- Verify that the detection zones are still in the proper location relative to the traffic lanes,
- Assess the impact of seasonal changes in the sun's position on detection accuracy,
- Verify that the video detection system is using the latest software version and upgrade it if needed, and
- Check the camera lens for moisture or dirt buildup and clean if needed.

With regards to higher level control algorithms, a performance evaluation was undertaken on a SCATS installation in Las Vegas. Arterial performance between the SCATS system and conventional Time of Day (TOD) coordination plans was compared; no significant improvement was found with the SCATS system. This SCATS system was driven by video detection, and the authors speculated that this might have limited the performance of SCATS *(Tian et al. 2011).*

2.1.2.2 Video Detection: Visible and Infrared Spectrum

In recent years, several manufacturers have brought units to market that utilize the infrared as well as visual spectrums for video detection. Researchers at Purdue University evaluated a unit side by side with a video detection system using inductive loops used for ground truth *(Grossman et al. 2012)*. The performance of the infrared system was consistent with the video system with one exception: activation times compared between day- and nighttime operations showed virtually no change. This is promising in that the infrared technology can help mitigate the effect of the headlight bloom, which is the reflection of vehicle headlights off of pavement, on night time video detection operations.

2.1.2.3 Radar Detection

Radar technology has been in use for the development of vehicle performance measures on freeway facilities for a number of years, however only recently have products been brought to market to employ this technology at signalized intersections. Earlier units focused on advance detection only, avoiding the inherent challenge of detecting vehicles at the stop bar with a technology that uses object motion to operate. Researchers at TTI tested a unit in 2008 and found that the unit accounted for a 23-48% increase in phase termination over video detection *(Middleton et al. 2008)*, which is perceived as an operational increase. Research personnel at Purdue noted that the use of this type of technology for advance detection has the potential to increase both efficiency and safety of dilemma zone protection since it tracks the vehicle all the way through the detection zone as opposed to extrapolating from an advance trap speed *(Sharma et al. 2008)*. Another research group noted that the units recorded speed and volume values comparable to loops during both free flow and congested conditions, although some occlusion issues were noted *(Minge et al. 2010)*. Investigation into the performance of these units under varying environmental conditions has been conducted, with the researchers noting that an increase in precipitation was correlated to performance degradation *(Medina et al. 2013, Ramesh et al. 2012)*. This research is noteworthy in that it tested newer units designed to provide both advance and stop bar detection. In favorable weather conditions, false and missed calls ranged from 0.4% to 6.1% of vehicles.

With regards to control, one study was undertaken to quantify the impact that the use of an advance radar unit has on safety and efficiency, but nothing was discussed regarding higher level control algorithms *(Sharma et al. 2011)*.

2.1.2.4 Other Non-Invasive Technologies

Recently, several manufacturers have developed a product that combines video and radar detection into one unit *(Econolite 2014)*. The video technology processes the stop bar detection while the radar monitors advance detection zones, capitalizing on the strengths of each technology. No work has been found regarding the evaluation of this, or similar products.

While other technologies, including laser and acoustic detection, have been deployed with varying degrees of success for traffic monitoring, their use thus far has been limited to vehicle counts and classification, and the use of these technologies to drive the inputs of an intersection is not known. Therefore, no literature regarding these technologies is presented.

2.2 OTHER RELATED DETECTION DISCUSSION

NCHRP Synthesis Project 403 investigated adaptive traffic control systems both domestic and abroad *(Stevanovic 2010)*. The majority of agencies surveyed (93%) used inductive loops, with 43% employing video detection as well. The report was not clear if the overlap is a result of planned redundancy or hybrid installations. The authors recommended that prior to selection and installation of an adaptive system, that the owners of that system investigate the detection requirements of the system, and evaluate what technologies will provide the necessary accuracy for the system to operate properly. The report did query practitioners about how their system operates when experiencing detection problems, but the discussion was very high level, and did not delve into the fine details of detection accuracy.

2.3 LIFE CYCLE COST ANALYSIS

2.3.1 Life Cycle Cost Analysis in Transportation

In recent years, several researchers from San Jose State University have undertaken life cycle cost analyses in relation to transportation. One such work presented the findings from an evaluation and economic analysis of the literature on benefit-cost estimates of public transit systems in the United States *(Ferrell 2015)*. This paper collected all the life cycle costs and benefits by types and compared urban and rural areas as well as by size. Some of the key benefits found in this study include decreased traffic congestion, economic stimulus and job prosperity, money savings for individuals, air quality enhancement, and reduced traffic fatalities *(Ferrell 2015)*. This paper also presented methods and equations relating costs associated with transportation projects and associated user costs for an urban vs rural comparison.

Another transportation cost analysis was conducted to estimate the economic benefits of transport investments in Sydney, Australia. This study explores gross domestic product (GDP) impacts from transportation investments, as well as the wider economic benefits as a result of a real project *(Legaspi et al. 2015)*. The study indicates that the widespread economic benefits represent an 8% increase over typical economic user benefits in benefit-cost calculation, with the latter encompassing value of travel time savings, reduction in accidents, and road decongestion *(Legaspi et al. 2015)*. This research provided a broad spectrum of economic benefits of transportation projects, including information regarding benefits and costs of transportation projects.

One study by researchers of Delft University of Technology formulated a trade-off analysis method for transportation investment decision making. This study focused on the decision making process of a project with conflicting preferences from multiple stakeholders. The authors recognize that most optimization techniques have not included impacts on the total economic benefits by altering a few key decision factors such as distinguishing relative importance of several transportation performance objectives, different types of facilities, and further reducing budget constraints implemented by transportation agencies *(Mouter et al. 2015)*. The research introduces a trade-off exploration that uses transportation network models to estimate the benefits of implementing a project based on the anticipated benefits. This paper provides both an analysis of life cycle costs and benefits within a system, along with their appropriate measures, and a conclusion that the trade-off approach introduced may increase total benefits by 18-20% *(Mouter et al. 2015)*.

Through a state developed initiative, researchers developed a life cycle cost analysis tool for the Federal Highway Administration which evaluates multiple new transportation technologies at the State level *(Bohmholdt and Weiss 2015)*. This tool provides results that can support technology installation by any State Department of Transportation. The tool provides general guidance on cost-effectives of implementing freight-related transportation technology at expense of State resources *(Bohmholdt and Weiss 2015)*. The tool is designed to evaluate the new technology's economic, social, and environmental impacts. This paper was prepared as a user's guide to provide agencies with an understanding how to use their benefit-cost analysis tool.

In the report published by the National Cooperative Highway Research Program (NCHRP) *Estimating the Life-Cycle Cost of Intersection Designs*, researchers developed a spreadsheet-based tool that can be used by a practitioner to compare the life-cycle costs of alternative designs for new and existing intersections. The spreadsheet tool was developed in a manner that allows the user to specify a number of options including lifespan, analysis period, traffic demand parameters, type of intersection, and alternative costs *(Rodegerdts 2015)*. They present several case studies which compare and contrast the benefits and costs associated with various types of intersections including signalized and roundabout controlled intersections. This report does not consider the case of adaptive control and rather focuses on intersection control type and user characteristics that are outside the scope of the current research.

2.3.2 Adaptive Signal Control Cost Studies

Recently, several reports and journal articles evaluating adaptive signal control systems and their costs and benefits have been published. One report evaluated the Virginia Department of Transportation's Adaptive Signal Control Technology pilot project. Researchers computed a benefit-cost ratio for each adaptive signal control site to assess whether the deployment produced an overall net benefit *(Fontaine et al. 2015)*. The Virginia Department of Transportation Traffic Engineering Division provided the researchers with costs associated with the initial purchase and installation of an adaptive signal control system. Costs included computer systems and the corresponding software, detection upgrades, and communication upgrades prior to adaptive signal control activation *(Fontaine et al. 2015)*. However, this study did not include ongoing maintenance costs supplementary to system deployment as the researchers claimed the data could not be easily isolated. The report produced both an equation to calculate benefit-cost ratios and the corresponding results, but the benefit-cost ratios shown may be "optimistic."

Similar research was conducted to analyze an adaptive traffic signal control system (ACS-Lite) for Wolf Road in Albany, New York. The study of this research project was the deployment and evaluation of an adaptive signal control system, ACS-Lite, on a congested urban corridor in New York State. Primary goals included documenting experiences and lessons learned from deployment and evaluation regarding initial setup, pros and cons of the system, and its suitability for installation in other corridors in New York *(Xuegang et al. 2014)*. A key aspect of this report was a benefit-cost analysis based on vehicular volumes, vehicular delay, consumption of fuel, and emissions data from peak traffic periods. The authors describe how they measured each variable including monetary values for value of travel time, value of fuel, and value of tailpipe emissions *(Xuegang et al. 2014)*. Although this paper presents compelling evidence of positive benefit-cost ratios from adaptive signal deployment, the researchers do not consider varying types of detection, their associated maintenance costs, and how they may affect the overall system performance.

Researchers from the University of Washington presented criteria for the selection and application of advanced traffic signal systems. Completed for the Oregon Department of Transportation (ODOT), this report addresses performance measurement and selection for adaptive signal control system installation *(Wang et al. 2013)*. Developed for practitioners, they implemented a survey which indicated engineers mostly wanted to know when and how to implement adaptive systems. The structure uses queuing models and simplified control logic to approximate corridor performance. Additionally, the researchers implemented a cost to benefit ratio calculation to compare performance across various systems and different measures of effectiveness *(Wang et al. 2013)*. Although the research attempts to include as many cost factors as practical, the Excel-based implementation of selection is intended to be as straight-forward as possible and does not indicate any life cycle cost changes due to varying detection selection for running the adaptive system.

One study focused on the long-term benefits of adaptive traffic control under varying traffic flows during weekday peak hours. Typically the evaluation of adaptive traffic control systems relies on data from short periods before and after installation. This paper reports projected long-term benefits of deploying an adaptive traffic control system, including statistical processing and modeling in microsimulation *(Stevanovic et al. 2012)*. The final results showed that the Sydney Coordinated Adaptive Traffic System (SCATS) outperformed existing time of day signal-timing plans by about 20% *(Stevanovic et al. 2012)*. This paper concluded that the monetary value of realized benefits showed that limited functioning benefits, projected over the long term, exceed overall installation costs for SCATS. However, this research did not incorporate various detection technologies in their evaluation of SCATS.

Another research project focused on before/after studies of adaptive signal systems in Pinellas County Florida. This study established cost-benefit ratios and summarizes lessons learned from the first stages of adaptive signal control system deployment *(Moser 2011)*. The information contained within the report aids in determining ways that adaptive systems may be improved. The paper specifically addresses recent changes in money saving deployment measures and improvement to adaptive algorithms as well as overall efficiency in maintenance and operation of the system. This paper does not compare various detection technologies, but does discuss improvements in comparison to new deployment costs.

In another project, *Evaluation of Vehicle Detection Technologies for Applications in Georgia,* researchers identified the circumstances appropriate for different detection technologies in adaptive signal control technologies. As an aspect of their research, the authors conducted a life cycle cost analysis of the technologies from which they collected high resolution field data. An agency survey was conducted through the Georgia Department of Transportation (GDOT) to assess nontechnical performance criteria such as life cycle cost and ease of installation and maintenance. They used the survey results to construct a multi-criterion framework to evaluate vehicle detection technologies using technical and nontechnical performance criteria *(Yang et al. 2015)*. Based on their results and findings, the researchers propose specific guidelines for adaptive systems and their corresponding vehicle detection. The life cycle costs in this current research paper mirror the methods used in the GDOT project as they were collected from manufacturers and distributors. However, the GDOT report provides their results in a multicriteria evaluation which results in weights to compare detection. No connection was made between specific Adaptive Signal Control Technologies ASCT technologies and deployment of the identified detection types.

One final report presents a decision support tool for the evaluation and selection of adaptive traffic control strategies. The authors argue that transportation agencies should carefully determine optimal locations for adaptive signal control strategies to maximize their benefits *(Mudigonda et al. 2008)*. This study uses a decision support system that can recommend the best network location for deployment of an adaptive signal system control strategy.

2.3.3 Operations and Maintenance

Operational and maintenance performance and cost are vital components to long term analysis of any adaptive signal control technology. While these systems may be capable and preferred for mitigating immediate traffic congestion, their annual operation and maintenance costs may be detrimental in the long term to the deploying agency. According to the Federal Highway Administration (FHWA), the selection process that is suggested when determining if an ASCT is appropriate, and which system should be chosen, requires an examination of life-cycle issues including operations and maintenance costs *(Gordon and Tighe 2005)*. Additionally, previous studies have identified specific ASCT technologies, SCATS, ACS-Lite, and InSync, that practitioners should be considering for deployment based on lower operational costs and decreased maintenance needs *(Seling and Schmidt 2010)*. However, these studies only included ASCTs that had sufficient data for comparison sake, and did not include systems that lacked data. Another study shows that agencies implementing ASCT require different personnel strategies than typical call and extend operations. The agency personnel strategies switch from a maintenance heavy focus to an operational focus *(Stevanovic 2010)*. Therefore, operations and maintenance are both key factors when considering complete life cycle costs of ASCT systems.

2.4 ONGOING RESEARC PROJECTS

During the development of the workplan for this project, three active research projects were identified that might have some similarities with the work being undertaken in this project. The Principal Investigators (PI) of these projects were contacted regarding the scope of their projects to inquire as to whether or not there is overlap. These projects and the results of the communication are as follows:

1. Idaho DOT: *Traffic Detection Systems Performance Evaluation*

    a. This project is testing different detection systems side by side to determine the level of accuracy and type of errors experienced under different light and weather conditions. Video, radar, hybrid video-radar, microwave, and other technologies will be evaluated. This project was completed in Spring of 2016. Dr. Smaglik spoke with the PI of this work in April 2016, and the results seen regarding detector performance in the Idaho project are in line with those identified in SPR 781.

2. Purdue NEXTRANS: *Increasing Accuracy of Vehicle Detection from Conventional Vehicle Detectors - Counts, Speeds, Classification, and Travel Time*

    a. This project focused on speed and length measurements from dual loops on freeways, and specifically the impacts of acceleration. It is not directly applicable to this work.

3. Louisiana DOT: *DOTD Support for UTC Project: Traffic Counting Using Existing Video Detection Cameras*

    a. The goal of this project is to assess the performance of video units in detecting traffic under varying weather conditions, with no focus on control. A research database search shows that this project is still active as of the writing of this report.

2.5 PRACTITIONER QUESTIONAIRE

As part of the literature review, several agency practitioners were surveyed as to whether or not any policies were in place to address poor detection performance. The following questions were posed via email to the practitioners listed in Table 2.1. Individuals selected to receive the survey represent a sample of practitioners managing traffic signals in areas of varying population, weather, and geography. The sample is by no means inclusive of all types of jurisdictions.

1. What type of detection technologies does your agency primarily deploy and operate (loop, radar, video, etc.)?

2. What type(s) of control do you predominantly use on your system (actuated coordinated, traffic responsive, adaptive, etc.)?

3. It is well known in practice that detection accuracy and latency can vary greatly with different detection technologies. Are there any policies and/or procedures in place, either formal or informal, to address the impact that less than perfect detection can have on intersection performance?

Table 2.1: Question Recipient List

Agency	Response?
Clark County, Washington	Yes
Clackamas County, Oregon	Yes
Indiana DOT	Yes
City of Mesa, AZ	Yes
City of Portland, OR	Yes
Minnesota DOT	Yes
City of Minneapolis	No
Hennepin County, Minnesota	Yes

As would be expected, the responses varied by agency. Below is a summary of the responses received for each question:

1. Two agencies, Indiana DOT and Minnesota DOT only use inductive technologies for detection. All other agencies use a combination of video, loops, and / or radar. Washington County noted that they are testing a bicycle micro-radar product marketed by Sensys. Clackamas County commented that they have recently switched from deploying only video to a combination of video, loops, and radar. Hennepin County has historically used loops, but is installing video for new needs. Portland typically uses loops, but will deploy video and radar in locations where loop installations are not practical (bridge decks, etc.)

2. With the exception of Clackamas County, all agencies contacted are running actuated coordinated with Time of Day operation on at least some percentage of their facilities (Clackamas County runs traffic responsive on one arterial, while all others are either free or actuated coordinated). Mesa and Portland currently operate at least one adaptive system. Clark County is in the process of installing a centralized traffic responsive system and an adaptive technology on three signals.

3. None of the agencies contacted have formal policies to address less than perfect detection, although a number have informal procedures.

    - Minnesota verifies the operation of its loops during an annual inspection of each intersection.

    - Clackamas County has been moving from video to a combination of loops and radar due to performance issues caused by shadows and other environmental conditions. They also noted that they need to verify the accuracy of existing video detection on corridor they are planning to upgrade to adaptive, given the dependence an adaptive system on accurate detection.

    - Portland prioritizes repair of broken detectors based upon the value of the detection at any given location. For example, a detector serving a heavy left turn movement would be a higher priority than a middle lane loop on a through movement.

    - Clark County employs comprehensive detection fault management to identify any detection issues for quick resolution.

    - Indiana developed a detection specification to address this issue *(Indiana Department of Transportation 2008).*

2.6 LITERATURE REVIEW SUMMARY

This literature review has investigated the current state of the research in vehicle detection technology, similar ongoing research projects, practices employed by practitioners to manage vehicle detection performance, and life cycle cost analyses. The overarching goal of this research project is to provide guidance for the use of non-invasive detection used within an adaptive or traffic responsive traffic control system. The following items were notes that specifically relate to that goal.

- Detection performance

    - The Indiana DOT has developed a performance specification for vehicle detection, addressing false calls, missed calls, and latency, among other things. To date, only inductive detection sources (loops and magnetometers) have met the specification.

- The performance of video detection has improved as the technology has matured, but its performance is still impacted by environmental conditions.

- Video detection utilizing visible and infrared spectrum has shown performance similar to legacy video detection, with the exception of more consistent activations times between day and night.

- Radar detection has been shown to be promising for advance detection, especially in that it can track a moving vehicle all the way through the detection zone, however research has shown that environmental factors can degrade the performance of this technology. Recent work examined the performance of radar units designed for stop bar detection and found that the units did experience missed and false calls.

* Research relating detector performance to higher level control strategies

  - Research is extremely limited in this area. One study looked at the performance of a SCATS system driven by video detection and found that performance was no better than the legacy system it replaced. The researchers felt the video detection might be the cause of the poor performance of the SCATS system, but did not specifically investigate this connection. No other work was found in this area.

* Life Cycle Cost Analysis in Transportation

  - Transportation improvement projects decrease traffic congestion, stimulate economy growth, mitigate emissions and environment damage, and reduce loss due to fatalities.

  - Most research has not included economic impacts by altering a few key decision factors.

* Adaptive Signal Control Cost Study

  - Research is limited in this area. One study looked at a cost benefit analysis with a weighting scheme, but did not present life cycle costs of ongoing maintenance and operation costs. No connection was made between specific ASCTs and deployment of various detection strategies.

  - As more transportation agencies begin to employ adaptive signal system technologies in their networks, the need to measure the costs and benefits associated with not only employing adaptive systems, but the decisions as to which vehicular detection should be selected for the system, becomes more pressing.

* Operations and Maintenance

  - Determining if an ASCT is appropriate requires an examination of life cycle issues including operations and maintenance costs.

  - Previous research shows that certain ASCT systems should be chosen based on lower operational costs and long term maintenance needs.

- Other ongoing research

  - Two other ongoing research projects are investigating the performance of non-invasive detection systems. The PI of the project funded by the Idaho DOT has shared his findings with the research team, and they are in line with those presented in this report.

- Practitioner policies relating to detection performance

  - Of the practitioners questioned, none have specific policies to deal with less than optimal vehicle detection performance. Several have informal methods of addressing this, however these center around understanding the limitations of specific technologies and deploying them based upon their strengths.

In summary, while the performance of non-invasive detection products has improved as the technologies have matured, there are still documented performance issues. These issues impact how practitioners choose to deploy detection technology, as well as continue to be the basis of funded research work to explore the extents of these performance differences. While many of these issues have been studied in depth and the impacts of them on call and extend control operation discussed, the effect of detection performance degradation on higher level control algorithms has not been explicitly addressed. Transitioning to economic factors, Life Cycle Cost Analysis (LCCA) is a tool that has been proven in many varied transportation economic analyses, and it has been applied in several formats to adaptive control. This research will apply proven methods, discussed in the next section, to quantify the operational effects of non-invasive detection on adaptive control inputs as well as investigate the cost differences of various adaptive control and detection strategies.

2.7 METHODOLOGY

The methodology of this work is as follows:

1. Collect high-quality event based data at signalized intersections with redundant detection (i.e. more than one technology monitoring an approach). Items to be collected include interval on/off times, detector on/off times, and concurrent video. Data is to be collected under various operational and geometric conditions, as well as varying control regimes.

2. Verify proper operation of inductive loops through a ground truth process.

3. Use operation of paired sensors to developed qualitative and quantitative (if possible) guidance for deployment on non-invasive detection within an adaptive system.

4. Conduct a cost comparison of invasive and non-invasive detection devices within the construct of various traffic control strategies, adaptive included.

2.7.1 Data Collection

Event based data with event states overlaid on concurrent video is perhaps the most effective method of collecting field data at signalized intersections. The lack of aggregation allows investigators to recreate field conditions from individual events through data mining procedures. The concurrent video allows researchers to visually correlate events identified through data mining with actual field behaviors. This type of data can be developed through video detection units *(Smaglik et al. 2005)*, a traffic controller *(Smaglik et al. 2007)*, or through logging of contact closures with external equipment. Details of the site selection process are presented in Chapter 3.0.

Given that there is no event based data logger already developed for the Northwest Signal (NWS) Voyage platform, the research team will develop one, including hardware and software modules, for this project. The details of this will be covered in Chapter 4.0.

2.7.2 Loop Operation

The data analysis methods employed by this project operate on the premise that the inductive loop is operating properly. As such, each inductive loop will go through a ground truth process to determine whether or not it is working as it should. In addition, as data is analyzed on a meta level, any sensors that seem to have systemic problems will be identified as well. This will be covered in Chapter 5.0.

2.7.3 Data Analysis

In Chapter 6.0 and Chapter 7.0, data collected from advance and stop bar detectors, respectively, will be analyzed. Analysis techniques will be both qualitative and quantitative in nature, using quantile regression, linear regression, and multinomial logit mathematical models to develop recommendations for deployment of non-invasive detection devices. Multiple metrics for advanced and stop bar detection will be analyzed.

2.7.4 Cost Comparison

Using cost data gathered from TAC members as well as vendors, a life cycle cost analysis will be conducted to determine differences in total lifetime costs for various detection devices and control strategies. Differences in cost will be related to user costs using values provided in established literature. Given that performance data (vehicle stops, delay, conflicts, and / or crashes) was not collected at any field location during this study, it is not possible to provide actual numerical comparisons of the devices studies in this work, however the method of using costs listed in established literature along with expected performance changes for comparison has been used in prior works *(Sharma et al. 2011, Sharma et al. 2007, Sharma et al. 2017)*. Analysis of the results of this quantitative comparison will also include a qualitative discussion, necessary given that different detection devices have different capabilities. This will be covered in Chapter 8.0.

At the conclusion of the cost analysis, recommendations, conclusions, and suggestions for future work will be presented in Chapter 9.0.

3.0 SITE SELECTION

The key element for site selection in this project required each site to have multiple detection technologies covering one or more approaches. Ten total sites around Oregon were visited and subjected for review. Among the sites visited, four sites were chosen for this project as they met all or most of the key criteria. The sites selected required minimal additional work while providing the most ideal conditions. The following chapter outlines the key criteria for the selection of each site and identifies the sites selected and their characteristics.

3.1 SITE SELECTION KEY CRITERIA

Several prospective sites were considered and reviewed for this project. The technical advisory committee was solicited in the selection process and assisted in identifying the locations that were critical to this research. Additionally, as part of the review process each intersection was analyzed using key criteria identified at the onset of the project. Focus was placed on intersections operating the advanced features of the Voyage software platform using video detection since this is the most common application of advanced intersection control in Oregon. However, all combinations of invasive and non-invasive detection were considered at adaptive signal locations. Additional consideration was given to locations with detection and cabinet solutions that aided in the collection and management of performance measure data. These key criteria included detection equipment in place, traffic controller in use, type of signal timing running, and traffic volumes. The following is a list of the key criteria considered when determining the sites for this project:

- Traffic control algorithm in use
- Availability and type(s) of redundant detection sources at the intersection
- Traffic volumes
- Type 2070 signal controllers

3.2 SELECTED SITES

Ten sites were subjected to a thorough review and four sites were selected. The four locations selected provided datasets to analyze video and advance radar detection versus inductive loop detection under varying traffic conditions. Additionally, they met the key criteria identified and required only minimal upgrades.

3.2.1 Town Center Loop West and SW Wilsonville Rd

The intersection of Town Center Loop West and Southwest Wilsonville Road is owned by the City of Wilsonville, OR and operated by Clackamas County, OR. The intersection is controlled using Voyage software and coordinated timing plans. This four legged intersection has moderate to high traffic volumes. The intersection is controlled by inductive loop detection; however, Autoscope SoloPro video detection is still present and functional on three of four approaches, as it was used to drive the control at one point in time. Additionally, the availability of analog video in-cabinet eased the data collection. High traffic volumes at this intersection made this a valuable site to gauge detection and intersection performance in oversaturated conditions. A total of eight redundant zones were captured at this site. Figure 3.1 is an aerial of the intersection with the 8 paired detection zones shown. The size of the ring indicating a detection zone is proportionate to the size of the zone. VD## indicates the Voyage Detector number used to identify the zone within the controller. Table 3.1 lists these detection zones along with pertinent details regarding each zone. Personnel from Econolite visited the site to setup the video detection zones such that the video presence zone would emulate an inductive loop presence zone of the same size.

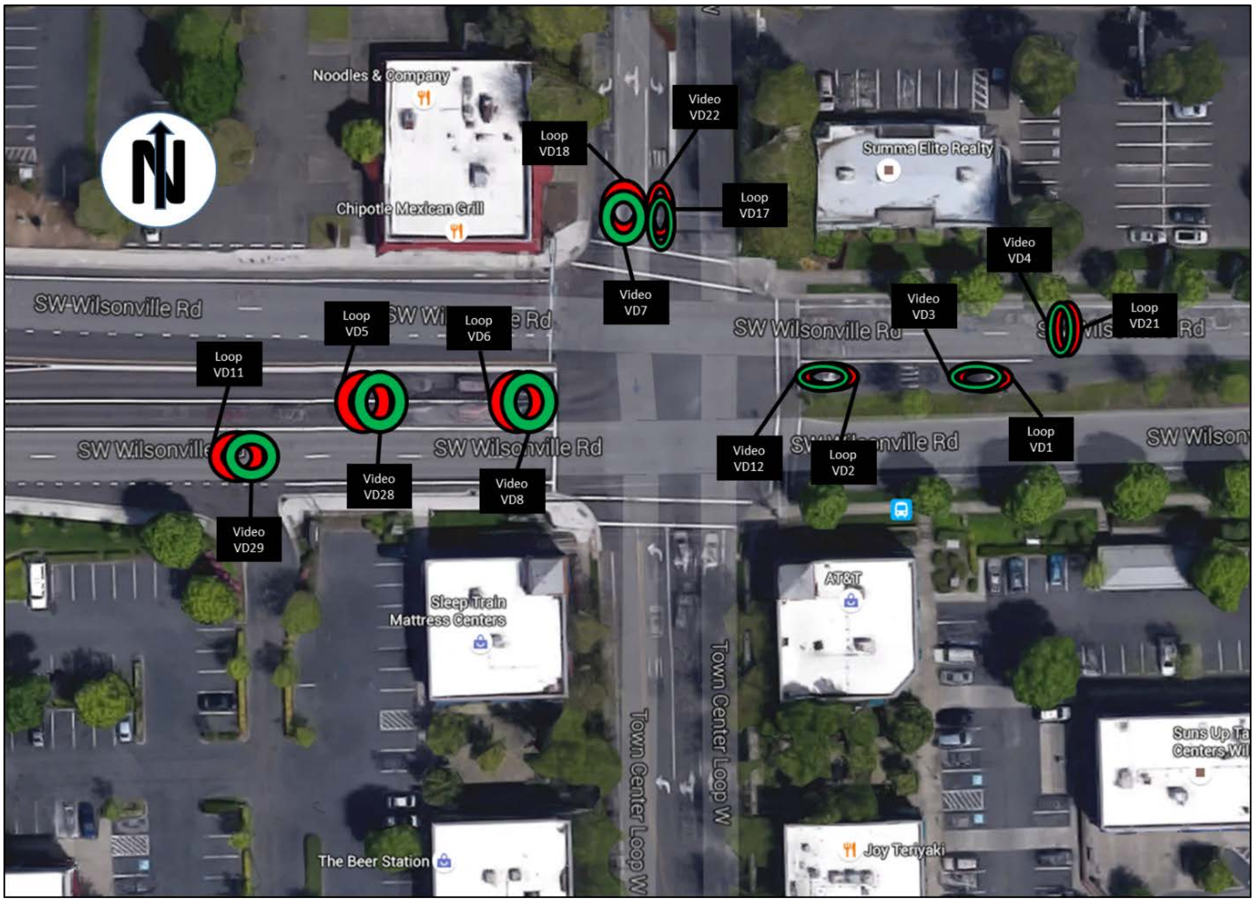


Figure 3.1: Overview of Town Center Loop West and Wilsonville Road Site

Table 3.1: Town Center Loop West and Wilsonville Road Detector Sizes and Zone Locations

Detector ID	Detector Length (ft)	Distance from stop bar to start of detection zone (ft)	Detector Type	Number of lanes	Lane Type	Direction of lane
TCLW_1_LOOP	15	75	Loop	1	Left	West
TCLW_2_LOOP	15	0	Loop	1	Left	West
TCLW_3_VIDEO	15	75	Video	1	Left	West
TCLW_34_VIDEO	8	110	Video	2	Thru	West
TCLW_5_LOOP	8	75	Loop	2	Left	East
TCLW_6_LOOP	15	0	Loop	2	Left	East
TCLW_7_VIDEO	15	0	Video	2	Thru	South
TCLW_8_VIDEO	15	0	Video	2	Left	East
TCLW_11_LOOP	8	110	Loop	2	Thru	East
TCLW_12_VIDEO	15	0	Video	1	Left	West
TCLW_17_LOOP	8	0	Loop	1	Left	South
TCLW_18_LOOP	15	0	Loop	2	Thru	South
TCLW_21_LOOP	8	110	Loop	2	Thru	West
TCLW_2_VIDEO	8	0	Video	1	Left	South
TCLW_28_VIDEO	8	75	Video	2	Left	East
TCLW_29_VIDEO	8	110	Video	2	Thru	East

3.2.2 SE 97th Avenue and SE Lawnfield Road

The intersection of SE 97th Ave and SE Lawnfield Rd is owned and operated by Clackamas County, OR. This four legged intersection has low to moderate traffic volumes and is controlled using Voyage software and runs free. This intersection is driven by inductive loop detection; however, Autoscope Oncore video detection is also installed on all approaches. In addition, Clackamas County installed a Wavetronix Matrix to monitor the southbound movements for the purposes of this study. Video is available via IP and since the intersection is driven by loop detection, the video cameras can be configured as necessary. Figure 3.2 shows an aerial of the site with the 12 pairs of vehicle detectors. Table 3.2 lists these detection zones along with pertinent details regarding each zone. As with the previous site, personnel from Econolite visited the site to setup the video detection zones such that the video presence zone would emulate an inductive loop presence zone of the same size.

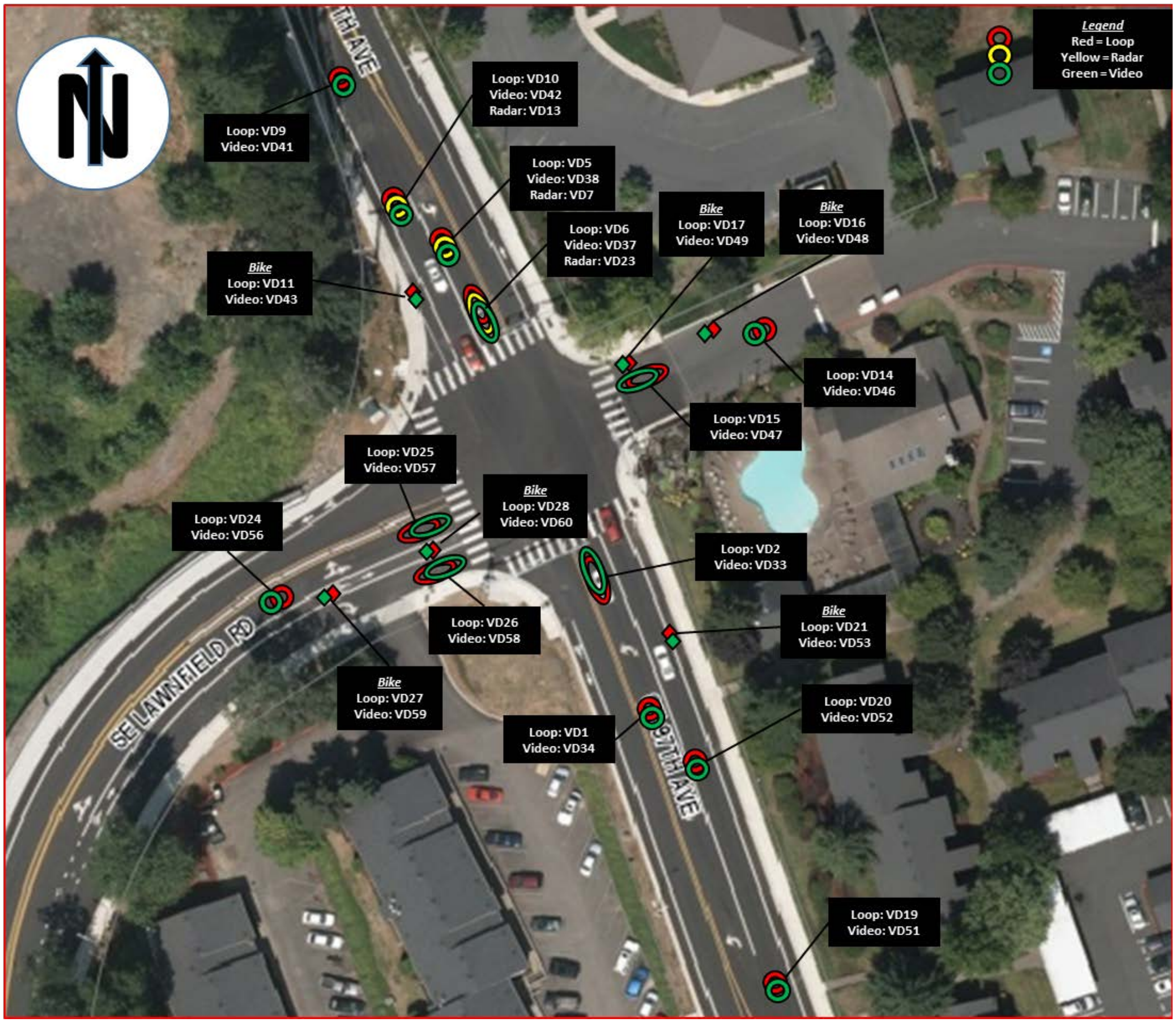


Figure 3.2: Overview of SE 97th Avenue and SE Lawnfield Road Site

Table 3.2: SE 97th Avenue and SE Lawnfield Road Detector Sizes and Zone Locations

Detector ID	Detector Length (ft)	Distance from stop bar to start of detection zone (ft)	Detector Type	Number of lanes	Lane Type	Direction of lane
97th_1_LOOP	8	75	Loop	1	Left	North
97th_2_LOOP	15	0	Loop	1	Left	North
97th_5_LOOP	8	75	Loop	1	Left	South
97th_6_LOOP	15	0	Loop	1	Left	South
97th_7_RADAR	8	75	Radar	1	Left	South
97th_9_LOOP	8	220	Loop	1	Thru	South
97th_10_LOOP	8	110	Loop	1	Thru	South
97th_11_LOOP	4	50	Loop	1	Bike	South
97th_13_RADAR	8	110	Radar	1	Thru	South
97th_14_LOOP	8	75	Loop	1	Left/Thru/Right	West
97th_15_LOOP	15	0	Loop	1	Left/Thru/Right	West
97th_16_LOOP	4	50	Loop	1	Bike	West
97th_17_LOOP	4	4	Loop	1	Bike	West
97th_19_LOOP	8	220	Loop	1	Thru	North
97th_20_LOOP	8	110	Loop	1	Thru	North
97th_21_LOOP	4	50	Loop	1	Thru	North
97th_23_RADAR	15	0	Radar	1	Left	South
97th_24_LOOP	8	75	Loop	1	Left/Thru	East
97th_25_LOOP	15	0	Loop	1	Left/Thru	East
97th_26_LOOP	15	0	Loop	1	Right	East
97th_27_LOOP	4	50	Loop	1	Bike	East
97th_28_LOOP	4	4	Loop	1	Bike	East
97th_33_VIDEO	15	0	Video	1	Left	North
97th_34_VIDEO	8	75	Video	1	Left	North
97th_37_VIDEO	15	0	Video	1	Left	South
97th_38_VIDEO	8	75	Video	1	Left	South
97th_41_VIDEO	8	220	Video	1	Thru	South
97th_42_VIDEO	8	110	Video	1	Thru	South
97th_43_VIDEO	4	50	Video	1	Bike	South
97th_46_VIDEO	8	75	Video	1	Left/Thru/Right	West
97th_47_VIDEO	15	0	Video	1	Left/Thru/Right	West
97th_48_VIDEO	8	50	Video	1	Bike	West
97th_49_VIDEO	4	4	Video	1	Bike	West
97th_51_VIDEO	8	220	Video	1	Thru	North
97th_52_VIDEO	8	110	Video	1	Thru	North
97th_53_VIDEO	4	50	Video	1	Thru	North
97th_34_VIDEO	8	75	Video	1	Left/Thru	East
97th_58_VIDEO	15	0	Video	1	Left/Thru	East
97th_57_VIDEO	15	0	Video	1	Right	East
97th_59_VIDEO	4	50	Video	1	Bike	East
97th_60_VIDEO	4	4	Video	1	Bike	East

3.2.3 US 20 and Robal Road

Located in Bend, OR, the intersection of US 20 and Robal Rd is owned and operated by ODOT Region 4. The signal is controlled using Voyage software and runs a free timing plan. This three legged intersection has moderate to high traffic volumes as well as high traffic speeds on the north and southbound approaches. The intersection is controlled by loops on the northbound and southbound approaches (US 20) and Traficon video detection on the minor approach (Robal Rd). An Iteris Vantage unit with advanced radar and stop bar video as well as a FLIR infrared unit were added on the southbound approach. Figure 3.3 is an aerial of this site, and shows the five redundant zones. Table 3.3 lists these detection zones along with pertinent details regarding each zone. Similar to the previous sites, vendor representatives from Iteris and FLIR visited the site to setup the non-invasive detection units such that their presence detection zones were the same size as the inductive loop presence detection zone.

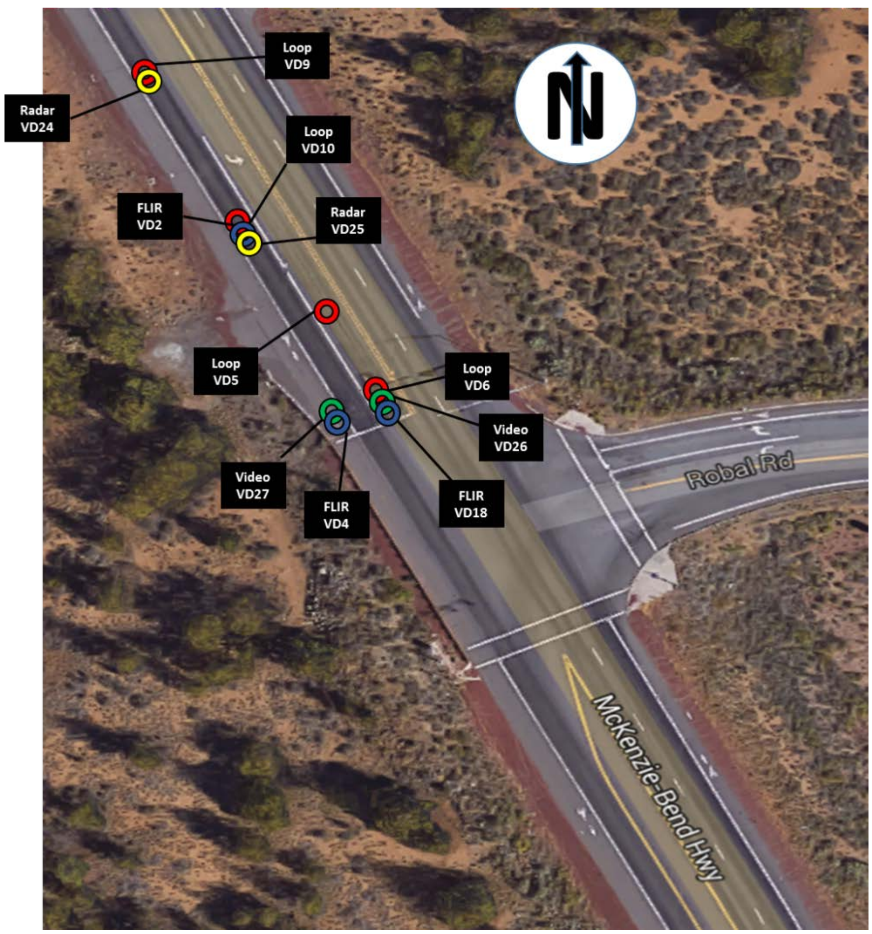


Figure 3.3: Overview of US 20 and Robal Road Site

Table 3.3: US 20 and Robal Road Detector Sizes and Zone Locations

Detector ID	Detector Length (ft)	Distance from stop bar to start of detection zone (ft)	Detector Type	Number of lanes	Lane Type	Direction of lane
US20_26_ITERIS	15	10	Video	1	Left	South
US20_24_ITERIS	6	460	Radar	1	Thru	South
US20_25_ITERIS	6	230	Radar	1	Thru	South
US20_27_ITERIS	6	10	Video	1	Thru	South
US20_18_FLIR	15	10	Infra-Red	1	Left	South
US20_2_FLIR	6	230	Infra-Red	1	Thru	South
US20_4_FLIR	6	10	Infra-Red	1	Thru	South
US20_9_LOOP	6	460	Loop	1	Thru	South
US20_10_LOOP	6	230	Loop	1	Thru	South
US20_5_LOOP	6	82	Loop	1	Left	South
US20_6_LOOP	15	12	Loop	1	Left	South

3.2.4 SE 122nd Avenue and SE Division Street

Located in Portland, OR, the intersection of SE 122nd Ave and SE Division St is owned and operated by the Portland Bureau of Transportation. This four legged intersection has high traffic volumes and moderate traffic speeds. Additionally, the intersection is controlled using Voyage software and runs either free or coordinated timing plans. The signal is controlled by inductive loop detection, however Econolite Terra video detection which was installed when the intersection was originally designed to be a test site, is also present on all approaches. Figure 3.4 is an aerial of the site and shows the sixteen redundant zones. Table 3.4 lists these detection zones along with pertinent details regarding each zone. As with the first two sites, personnel from Econolite visited the site to setup the video detection zones such that the video presence zone would emulate an inductive loop presence zone of the same size.

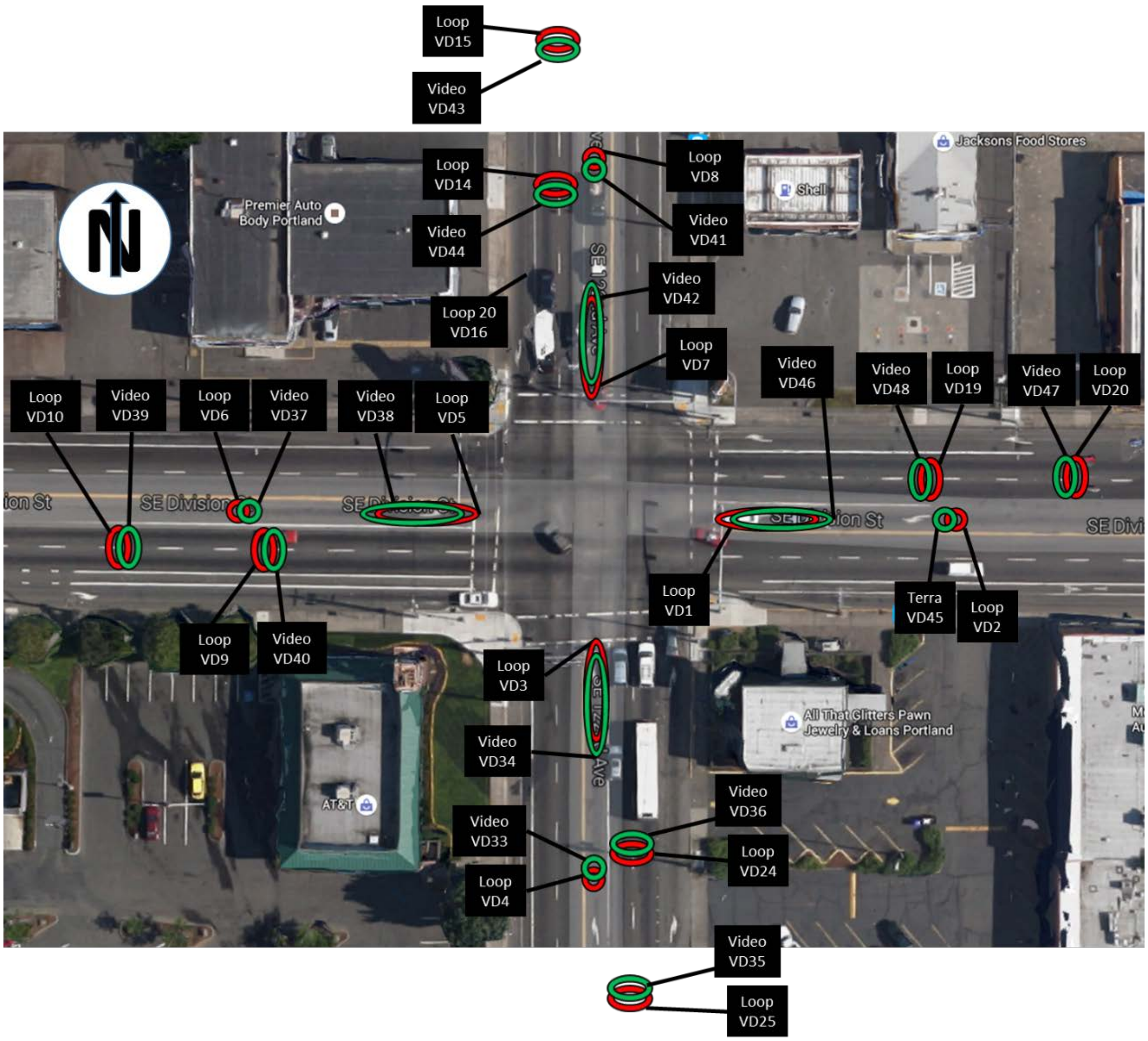


Figure 3.4: Overview of SE 122nd Avenue and SE Division Street Site

Table 3.4: SE 122nd Avenue and SE Division Street Detector Sizes and Zone Location

Detector ID	Detector Length (ft)	Distance from stop bar to start of detection zone (ft)	Detector Type	Number of lanes	Lane Type	Direction of lane
122nd_1_LOOP	33	0	Loop	1	Left	West
122nd_9_LOOP	6	85	Loop	1	Thru	East
122nd_10_LOOP	6	188	Loop	1	Thru	East
122nd_3_LOOP	33	0	Loop	1	Left	North
122nd_14_LOOP	6	85	Loop	1	Thru	South
122nd_15_LOOP	6	188	Loop	1	Thru	South
122nd_2_LOOP	6	102	Loop	1	Left	West
122nd_4_LOOP	6	105	Loop	1	Left	North
122nd_5_LOOP	33	0	Loop	1	Left	East
122nd_19_LOOP	6	86	Loop	1	Thru	West
122nd_20_LOOP	6	187	Loop	1	Thru	West
122nd_7_LOOP	33	0	Loop	1	Left	South
122nd_24_LOOP	6	88	Loop	1	Thru	North
122nd_25_LOOP	6	169	Loop	1	Thru	North
122nd_6_LOOP	6	100	Loop	1	Left	East
122nd_8_LOOP	6	103	Loop	1	Left	South
122nd_33_VIDEO	6	105	Video	1	Left	North
122nd_34_VIDEO	33	0	Video	1	Left	North
122nd_35_VIDEO	6	169	Video	2	Thru	North
122nd_36_VIDEO	6	88	Video	2	Thru	North
122nd_37_VIDEO	6	100	Video	1	Left	East
122nd_38_VIDEO	33	0	Video	1	Left	East
122nd_39_VIDEO	6	188	Video	2	Thru	East
122nd_40_VIDEO	6	85	Video	2	Thru	East
122nd_41_VIDEO	6	103	Video	1	Left	South
122nd_42_VIDEO	33	0	Video	1	Left	South
122nd_43_VIDEO	6	188	Video	2	Thru	South
122nd_44_VIDEO	6	85	Video	2	Thru	South
122nd_45_VIDEO	6	102	Video	1	Left	West
122nd_46_VIDEO	33	0	Video	1	Left	West
122nd_47_VIDEO	6	187	Video	2	Thru	West
122nd_48_VIDEO	6	86	Video	2	Thru	West

3.3 SITE SELECTION SUMMARY

The four sites utilized for data collection on this project employ inductive loops, video detection (four different units), radar detection (two different units), and infrared detection. A total of 47 redundant zones were monitored during the data collection phase of the project. At each site, prior to collecting data, a vendor or manufacturer's representative assisted the research team in configuring the non-invasive detection to emulate the respective inductive loop (this type of configuration was done at the request of the research team). A representative assisted in the configuration of all non-invasive zones; no zone was configured by only research or agency staff. The following chapter will describe the data logging device that was designed and built expressly for this project.

4.0 DATA COLLECTION

In order to capture data, a field PC installed with a data logging software was installed in the traffic cabinet at each site. The data logging solution consisted of hardware and software modules, which will be described in the subsequent sections. The module was designed with the objective of monitoring and recording the status of up to 64 detectors and all phases, while recording simultaneous video footage for later observation, as needed. Figure 4.1 illustrates the general structure of the data logging module. The status of all of the detectors is communicated to the controller via established cabinet communication protocols. A field PC records the states of these events as well as concurrent video streams. The end result is a digital and video log of all the event changes, detector and phase. The subsequent sections of this chapter introduce and explain the components of the data logger software and associated hardware.

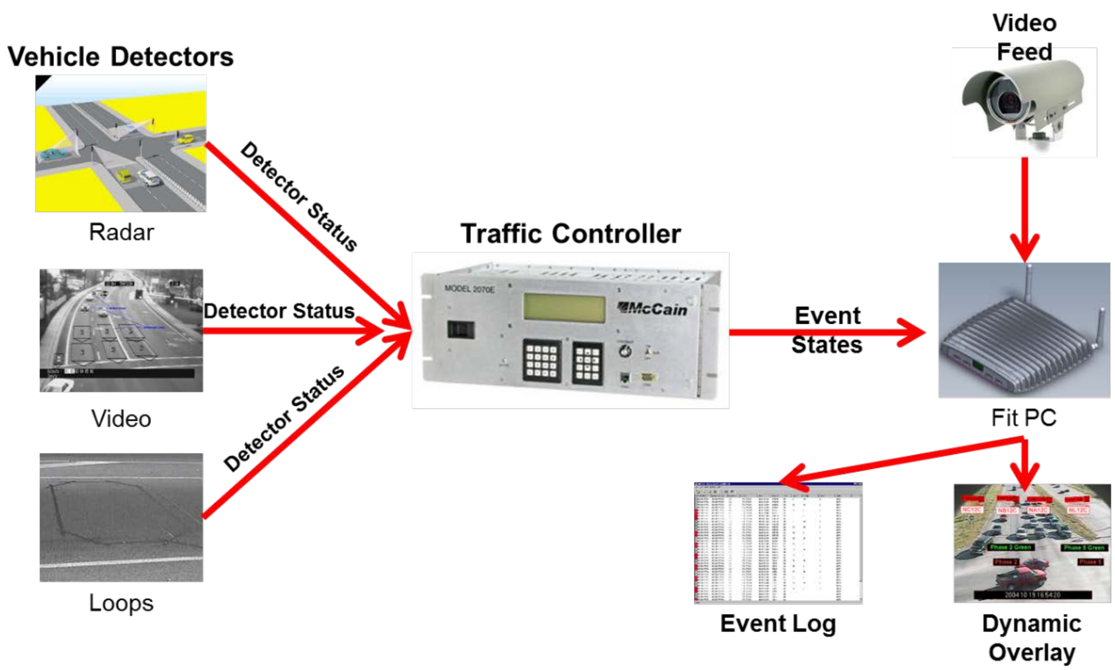


Figure 4.1: Data Structure of Logging Module

4.1 DATA LOGGING SOFTWARE MODULE

National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) defines many objects for actuated traffic signal controller (ASC) units using the OBJECT-TYPE macros *(National Transportation Communications for ITS Protocal 2005).* These objects include phase, detector, ring, and coordination parameters, and others than can be exchanged between controllers and computers via Simple Transportation Management Protocol (STMP) *(National Transportation Communications for ITS Protocal 2009).* The software developed for this work obtains the signal and detector parameters by intercepting the exchanged data. This software named TraSER (Traffic Signal Event Recorder), monitors red, yellow, and green indication statuses of 8 vehicle phases, pedestrian crossing signal statuses of 8 phases, and the detection statuses of 64 detectors, allowing for the statuses of all redundant detection zones to be captured for this project.

TraSER is a portable software application written in C++ designed to run on any NTCIP compliant signal controller. To utilize TraSER, the traffic controller is connected to hardware running TraSER through an Ethernet connection. TraSER consists of two modules: the signal and detector data collection module, and the screen capturing module. Figure 4.2 shows the overall graphic user interface for the program. The left side of the screen, the graphical user interface, shows the real time detector and signal statuses while the right side shows the simultaneous video footage captured from video surveillance cameras. All event data as shown in the user interface are archived in text files by time of day shown in Table 4.1.

Figure 4.2: Screenshot of the Running TraSER

Table 4.1: TraSER Data Log File

Date	Time	Data Type	No.	Status (1, on; 0, off)
6/25/2015	09:47:02.619	R	1	1
6/25/2015	09:47:02.619	G	2	1
6/25/2015	09:47:02.619	G	6	1
6/25/2015	09:47:02.619	DW	3	1
6/25/2015	09:47:02.619	DW	4	1
6/25/2015	09:47:02.619	DET	6	1

The sampling rate of TraSER is high enough to capture real-time data change (it is greater than the $1/10^{th}$ of a second resolution on which traffic controllers make decisions). Additionally, the signal and detector statuses can only be sent from the traffic controller to the field hardware, and not vice versa, making it impossible for TraSER to impact operation of the intersection.

4.1.1 Signal Data Collection Module

The signal and data collection module is the core of TraSER, a home grown software designed to collect event based signal and detector data. In this module, TraSER sends data requests to the traffic controller. Since the controller only responds once when it receives a data request, the software continuously sends and receives requests and responses, respectively, and then logs the data received.

The binary data are recorded in text files along with a timestamp by time of day as shown in Table 4.1. The 1st column and 2nd column show the date and time of events. The 3rd column shows the event types which would be either a signal phase status, pedestrian phase status, or status of a vehicle detector. The traffic signal statuses include Red (R), Yellow (Y), and Green (G). The pedestrian signals include Don’t Walk (DW), Walk (WA), and Pedestrian Clearance (PC). Detector statuses are represented by DET. The 4th column in the table shows the serial numbers of signals or detectors. The last column displays the statuses of signals or detectors. A ‘1’ indicates that a signal or detector call has turned on, and ‘0’ indicates that a signal or detector call has turned off. For example, in Table 4.1 the 1st record shows that vehicle phase 1 became red at 09:47:02.609, 06/25/2015, and the 6th record shows that the detector 6 was activated at 09:47:02.609, 06/25/2015. Data is saved in one-hour increments to prevent the files from becoming very large and causing stability problems.

4.1.2 Screen Capture Module

With controller data and a video camera feed displayed simultaneously, the second module was developed to record this information such that it can be viewed at a later date when analyzing the recorded data. To accomplish this, a third party open source tool - HyperCam 2 *(Hyperionics Techology LLC 2014)* was used to save the video into an Audio-Video Interleaved (AVI) movie file. Additional coding was used to start the video recording concurrently with the TraSER software as well as to save the video files in one-hour increments.

4.2 DATA LOGGING HARDWARE MODULE

TraSER requires a Microsoft Windows platform on which to run. To provide that, a semi-hardened field PC (brand name FitPC) was chosen as the platform. This device was chosen because of its ample digital storage as well as the fact that it has multiple I/O ports (8 USB, 2 NIC, and 2 Video, among others). This allowed for maximum installation flexibility. Video at two of the sites was provided via Ethernet, however video at the other two sites was analog. As such, an encoding device was needed to allow video to be recorded digitally. A 4:1 Axis video encoder was selected for this, as it had the capabilities to receive four analog channels and output any one of the channels, or all four as a quad view. Figure 4.3 shows a photo of the Fit PC (on the left) and the Axis encoder (on the right) mounted in one of the traffic cabinets. A custom mounting plate was fabricated such that the devices could be attached to the rack on the back side of the cabinet, such that they don’t interfere with the critical components in the signal cabinet.

Figure 4.3: FitPC and Axis Encoder

In addition to the hardware shown in Figure 4.3, various cables and connectors were used to allow the devices to interface with each individual cabinet, and an uninterruptible power supply (UPS) to provide a reliable power source for the units. As was noted earlier, TraSER communicates with the traffic controller via Ethernet. While all of the installations with this project involved equipment mounted inside the cabinet, the software could be operated remotely if ample communication bandwidth was available. In such a case, the video would also need to be accessible over IP to operate TraSER remotely.

4.3 DATA COLLECTION PROCESS

Two hardware modules were developed so that data could be collected simultaneously at multiple sites. The goal at the onset of deployment was to collect roughly two full weeks of data at each site, however because of various issues, additional data was collected at some sites, while less than two full weeks was collected at one site. Table 4.2 lists the total amount of data collected by site. The subsequent sections will identify any issues or problems.

Table 4.2: Data Collection by Site

Location	Data Collection Dates	Good Data
SW Wilsonville Road and Town Center Loop West	5/11/15 – 6/18/15	507 hours (21 days)
SE 97th Avenue and Lawnfield Road	6/18/15 – 7/28/15	599 hours (25 days)
US 20 and Robal Road	6/25/15 – 11/6/15	196 hours (8 days)
SE Division Street and SE 122nd Ave	10/20/15 – 11/16/15	626 hours (26 days)

4.3.1 SW Wilsonville Road and Town Center Loop West

Research personnel met with Clackamas County staff on May 11th, 2015 to install the data logging device into the cabinet. On May 18th, 2015, Clackamas County personnel returned to the site to make an adjustment to the video detections zones, so data prior to the 18th is not included in the study. The research staff met with Clackamas County personnel in regular intervals to download the data from the onboard hard drive of the FitPC, until its removal on June 18th, 2015. Problems that occurred at this site were minor; including several Windows pop ups that obscured the video recording, and insufficient hard drive storage space on the FitPC, which brought data recording to an end.

4.3.2 SE 97th Avenue and Lawnfield Road

Research personnel met with Clackamas County staff on June 18th, 2015 to install the data logging device into the cabinet. The data was downloaded from the Fit PC at regular intervals by the research staff until the device was removed on July 28th, 2015. Problems that occurred at this site were minor, and involved only one instance of a Windows pop up obscuring the video recording.

4.3.3 US 20 and Robal Road

Research personnel met with ODOT Region 4 staff on June 25th, 2015 to install the data logging device into the cabinet. At this point in time, the Iteris unit was calibrated and functional, however the FLIR unit was still slated to be installed and set up (this was finally completed in late summer). Over the period of roughly 5.5 months until data logging device was removed, this site experience multiple problems, several of them resulting in a loss of data. Twice the hard drive failed on the unit, and multiple times the FLIR unit stopped sending video data to the Fit PC. In addition, the outputs of the FLIR unit were incorrectly mapped in the controller, resulting in no performance data being collected for this device. After 5 ½ months in the field, approximately 8 days of usable data were obtained from this site.

4.3.4 SE 122nd St and SE Division Rd

Research personnel met with Portland Bureau of Transportation (PBOT) staff on October 20th, 2015 to install the data logging device into the cabinet. Several times from the install date until the device was removed on November 16th, 2015, research staff met with PBOT personnel on site to pull data from the onboard hard drive of the FitPC. Problems that occurred at this site were minor, and involved only one instance of the onboard digital storage filling prematurely due to a recording codec error.

4.4 DATA COLLECTION SUMMARY

While there were a handful of various issues encountered during the data collection, overall the data collection module designed and built for collecting event based data produced an archive of over 5 million detection events between 40 different sensor pairs, providing a robust set of data for analysis.

5.0 DATA COMPILATION AND VERIFICATION

While the final stages of data collection were being completed, analysis of the data had already begun. Historically, inductive loops, when working properly, are very precise and reliable. The data analysis in this work is designed around the premise that once shown to be working properly, the loops can be used as a baseline for performance of other detection devices *(Grenard et al. 2001, Rhodes et al. 2007)*. Given that the inductive loops at the four sites in this work are of varying ages and conditions, the first step was to verify the performance of these loops, and from there, proceed with the data analysis.

5.1 LOOP VERIFICATION PROCESS

All four data collection sites were subjected to a ground truthing process, the objective of which was to ensure that each loop or combination of loops worked reliably (activated on and off) compared to manual observation. This was performed by comparing the on and off activation times recorded by the loop to those obtained manually from the video. In order to perform this task, first a correlation matrix was constructed for each site from the detector layout plans that were provided by each agency. This matrix essentially linked the loop number to the Voyage detector number. An example of the correlation matrix is provided in Table 5.1 below.

Table 5.1: Loop Correlation Matrix for WB Approach at Division St. and 122nd Ave

Loop #	Voyage Detector #	Phase
1-4	1	1
23	2	1
29-30	19	6
31-32	20	6

Using this correlation matrix, the on and off times for each loop detector or pairs of detectors were extracted from the text file that was recorded by the data logger. To obtain the on and off times manually, an imaginary line was drawn on the screen for each detector. Using that line as a reference point, the time when a car crossed that line was noted along with the time, when the car exited that line. These two times were considered as the manual on and off times for the loop and were compared to those recorded by the loop. This process was undertaken for a 15-minute period for each loop or loop pair. In addition, the number of vehicles passing during the time when each loop call was held along with the type of vehicle was also noted. Table 5.2 shows an example of the ground truth process at Division St. and 122nd Ave.

Table 5.2: Example of Ground Truth Process at Division St. and 122nd Ave.

Date / Time	Manual GT(start)	Manual GT (end)	Loop Call (start)	Loop Call (end)	Number of Vehicles	Vehicle Type
10/30/2015 11:00AM-11:15AM					5	Personal
10/30/2015 11:00AM-11:15AM		11:02:14.155		11:02:13:205		
10/30/2015 11:00AM-11:15AM	11:02:50.024		11:02:49:717		6	Personal
10/30/2015 11:00AM-11:15AM		11:04:06.370		11:04:04:536		
10/30/2015 11:00AM-11:15AM	11:04:06.370		11:04:04:586		1	Personal
10/30/2015 11:00AM-11:15AM		11:05:51.258		11:05:50:089		
10/30/2015 11:00AM-11:15AM	11:05:51.477		11:05:50:755		2	Personal
10/30/2015 11:00AM-11:15AM		11:05:55.197		11:05:52:587		
10/30/2015 11:00AM-11:15AM	11:05:55.529		11:05:55:104		5	Personal
10/30/2015 11:00AM-11:15AM		11:07:44.794		11:07:43:904		
10/30/2015 11:00AM-11:15AM	11:09:15.464		11:09:15:013		2	Personal
10/30/2015 11:00AM-11:15AM		11:09:30.227		11:09:29:120		
10/30/2015 11:00AM-11:15AM	11:09:46.744		11:09:46:694		3	Personal
10/30/2015 11:00AM-11:15AM		11:11:20.368		11:11:19:445		
10/30/2015 11:00AM-11:15AM	111:12:17.352		11:12:16:579		2	Personal
10/30/2015 11:00AM-11:15AM		11:13:10.839		11:13:10:250		
10/30/2015 11:00AM-11:15AM	11:13:54.481		11:13:54:428		2	Personal
10/30/2015 11:00AM-11:15AM		11:15:01.527		11:15:00:407		

Additionally, incidences of missed and false calls were also noted. Missed calls were defined as those that were recorded by the manual ground truth process but were absent from the text file. False calls were defined as those that were recorded by the loop, but were absent from the ground truth process. Table 5.3 shows the summary of false and missed calls at Wilsonville Rd. and Town Center Loop West. The west bound advance loop in the left turn lane was found to miss all the calls during the ground truth process while the west bound left turn stop bar loop missed one. None of the loops recorded any false calls. Table 5.4 shows the summary of missed and false calls at 97th Ave. and Lawnfield Rd. A number of loops recorded both missed and false calls.

Table 5.5 shows the summary of missed and false calls at US 20 and Robal Rd. in Bend. At this location, the ground truthing was performed only on the south bound approach, as this was the only approach with redundant detection. The analysis showed that the south bound shared through and right turn near advance loop showed 3% missed calls, whereas three of the loops recorded false calls. Table 5.6 shows the summary of missed and false calls at SE. Division St. and SE. 122nd Ave. In general the loops at this location performed poorly, with most of them recording a high number of false calls. Missed calls at this location were rare in general.

For all sites, lines in boldface type indicate loops that passed the ground truth process.

Table 5.3: Summary of Missed and False Calls at Wilsonville Rd. and Town Center Loop West

Date / Time	Voyage Detector #	Location	Total Calls	Missed Calls	Missed Calls %	False Calls	False Calls %
5/18/2015 11:00 - 11:15	**11**	**EB TH/RT Advance**	**111**	**0**	**0%**	**0**	**0%**
5/18/2015 11:00 - 11:15	**5**	**EB LT Advance**	**109**	**0**	**0%**	**0**	**0%**
5/18/2015 11:00 - 11:15	**6**	**EB LT Stop Bar**	**110**	**0**	**0%**	**0**	**0%**
5/18/2015 11:00 - 11:15	**18**	**SB TH/RT Stop Bar**	**110**	**3**	**3%**	**0**	**0%**
5/18/2015 11:00 - 11:15	**17**	**SB LT Stop Bar**	**4**	**0**	**0%**	**0**	**0%**
5/18/2015 11:00 - 11:15	**21**	**WB TH/RT Advance**	**97**	**0**	**0%**	**0**	**0%**
5/18/2015 11:00 - 11:15	1	WB LT Advance	5	5	100%	0	0%
5/18/2015 11:00 - 11:15	2	WB LT Stop Bar	6	1	17%	0	0%

Table 5.4: Summary of Missed and False Calls at SE 97th Ave. and SE Lawnfield Rd.

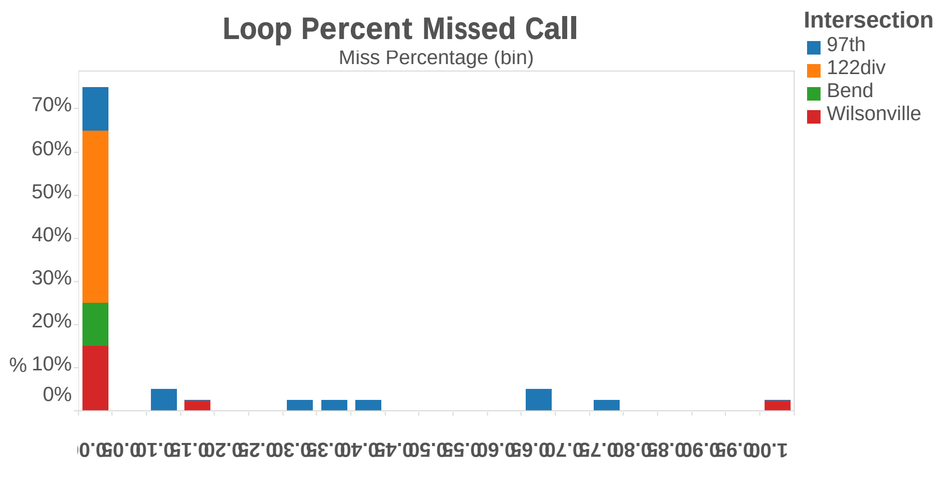
Date / Time	Voyage Detector #	Location	Total Calls	Missed Calls	Missed Calls %	False Calls	False Calls %
6/30/2015 11:00 - 11:15	**20**	**NB TH/RT Advance**	**36**	**0**	**0%**	**0**	**0%**
6/30/2015 11:00 - 11:15	1	NB LT Advance	8	0	0%	2	25%
6/30/2015 11:00 - 11:15	2	NB LT Stop Bar	8	3	38%	0	0%
6/30/2015 11:00 - 11:15	9	SB TH/RT Advance	63	6	10%	2	3%
6/30/2015 11:00 - 11:15	**10**	**SB TH/RT Advance**	**58**	**2**	**3%**	**1**	**2%**
6/30/2015 11:00 - 11:15	**5**	**SB LT Advance**	**4**	**0**	**0%**	**0**	**0%**
6/30/2015 11:00 - 11:15	24	EB LT/TH Advance	27	18	67%	1	4%
6/30/2015 11:00 - 11:15	25	EB LT/TH Stop Bar	34	4	12%	3	9%
6/30/2015 11:00 - 11:15	26	EB RT Stop Bar	12	5	42%	0	0%
6/30/2015 11:00 - 11:15	6	SB LT Stop Bar	4	3	75%	0	0%
6/30/2015 11:00 - 11:15	14	WB LT/TH/RT Advance	6	4	67%	0	0%
6/30/2015 11:00 - 11:15	15	WB LT/TH/RT Stop Bar	6	2	33%	0	0%

Table 5.5: Summary of Missed and False Calls at US 20 and Robal Rd.

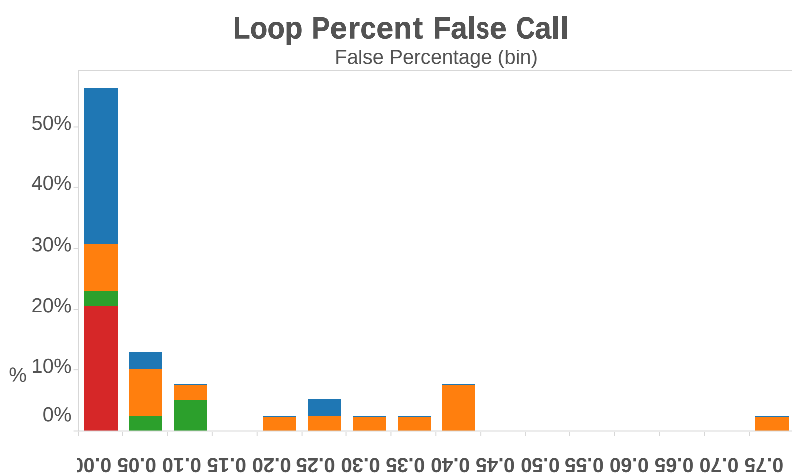
Date	Voyage Detector #	Location	Total Calls	Missed Calls	Missed Calls %	False Calls	False Calls %
10/8/2015 11:00 - 11:15	9	SB TH/RT Advance	136	0	0%	16	12%
10/8/2015 11:00 - 11:15	10	SB TH/RT Advance	130	4	3%	10	8%
10/8/2015 11:00 - 11:15	5	SB LT Advance	17	0	0%	2	12%
10/8/2015 11:00 - 11:15	**6**	**SB LT Stop Bar**	**20**	**0**	**0%**	**0**	**0%**

Table 5.6: Summary of Missed and False Calls at SE Division St. and SE 122nd Ave.

Date / Time	Voyage Detector #	Location	Total Calls	Missed Calls	Missed Calls %	False Calls	False Calls %
10/21/2015 11:00-11:15	1	WB LT Stop Bar	10	0	0%	4	40%
10/21/2015 11:00-11:15	**2**	**WB LT Advance**	**30**	**0**	**0%**	**1**	**3%**
10/21/2015 11:00-11:15	19	WB TH Advance	131	5	4%	31	24%
10/21/2015 11:00-11:15	20	WB TH Advance	78	0	0%	13	40%
10/21/2015 11:00-11:15	**5**	**EB LT Stop Bar**	**10**	**0**	**0%**	**0**	**0%**
10/21/2015 11:00-11:15	**6**	**EB LT Advance**	**22**	**0**	**0%**	**1**	**5%**
10/21/2015 11:00-11:15	9	EB TH Advance	109	1	1%	30	28%
10/21/2015 11:00-11:15	10	EB TH Advance	73	1	1%	11	15%
10/30/2015 11:00-11:15	3	NB LT Stop Bar	8	0	0%	40	500%
10/30/2015 11:00-11:15	4	NB LT Advance	29	0	0%	22	76%
10/30/2015 11:00-11:15	24	NB TH Advance	68	1	1%	21	31%
10/30/2015 11:00-11:15	25	NB TH Advance	78	1	1%	31	40%
10/30/2015 11:00-11:15	7	SB LT Stop Bar	11	0	0%	4	36%
10/30/2015 11:00-11:15	**8**	**SB LT Advance**	**32**	**0**	**0%**	**0**	**0%**
10/30/2015 11:00-11:15	**14**	**SB TH Advance**	**53**	**0**	**0%**	**4**	**8%**
10/30/2015 11:00-11:15	**15**	**SB TH Advance**	**88**	**0**	**0%**	**4**	**5%**



a. Percent Missed Call



b. Percent False Call

Figure 5.1: Loop Ground Truth Performance Summary

As can be seen in Figure 5.1, there is a natural break in the frequency distribution of missed calls and false calls at the 10% error level. This is chosen a threshold for anomaly detection for this research. If any loop has sum of missed calls and false calls greater than 10%, it was not included in conducting the performance comparison with non-invasive technology. This is based upon another study *(Smaglik et al. 2007)*, where a 10% accuracy was considered as a threshold for good loop performance. It should be noted that 42.5% of the 40 loops used in this study performed at an error rate of less than 10%. The poorly functioning loops were concentrated in two intersections, SE 122nd Avenue & Division Street (mostly false calls) and 97th Avenue & SE Lawnfield Road (mostly missed calls). These two sites were responsible for 15 of the 16 loops in the study with an error rate above 10%. As was noted earlier, these loops would be eliminated from the comparison. Table 5.7 lists the sensors that passed the ground truth, a total of 16 loops, including 11 advance sensors and 5 stop bar sensors. Figure 5.2, Figure 5.3, Figure 5.4, and Figure 5.5 summarize the outcome of the ground truth for each site, with the sensors that passed the ground truth verification indicated in green, and those that failed were designated in red.

Table 5.7: Loop Sensors Passing the Ground Truth Verification

No	Intersection	VD#	Direction	Location	Type
1	SW Wilsonville Rd & TCLW	11	EB	TH/RT	Advance
2		5	EB	LT	Advance
3		6	EB	LT	Stop bar
4		18	SB	TH/RT	Stop bar
5		17	SB	LT	Stop bar
6		21	WB	TH/RT	Advance
7	97th Avenue & SE Lawnfield Road	20	NB	TH/RT	Advance
8		10	SB	TH/RT	Advance
9		5	SB	LT	Advance
10	US 20 & Robal Road	6	SB	LT	Stop bar
11	SE 122nd Avenue & Division Street	2	WB	LT	Advance
12		5	EB	LT	Stop bar
13		6	EB	LT	Advance
14		8	SB	LT	Advance
15		14	SB	TH	Advance
16		15	SB	TH	Advance

Note:
1. EB: Eastbound; WB: Westbound; SB: Southbound; NB: Northbound.
2. LT: left-turn; TH: through; RT, right-turn.

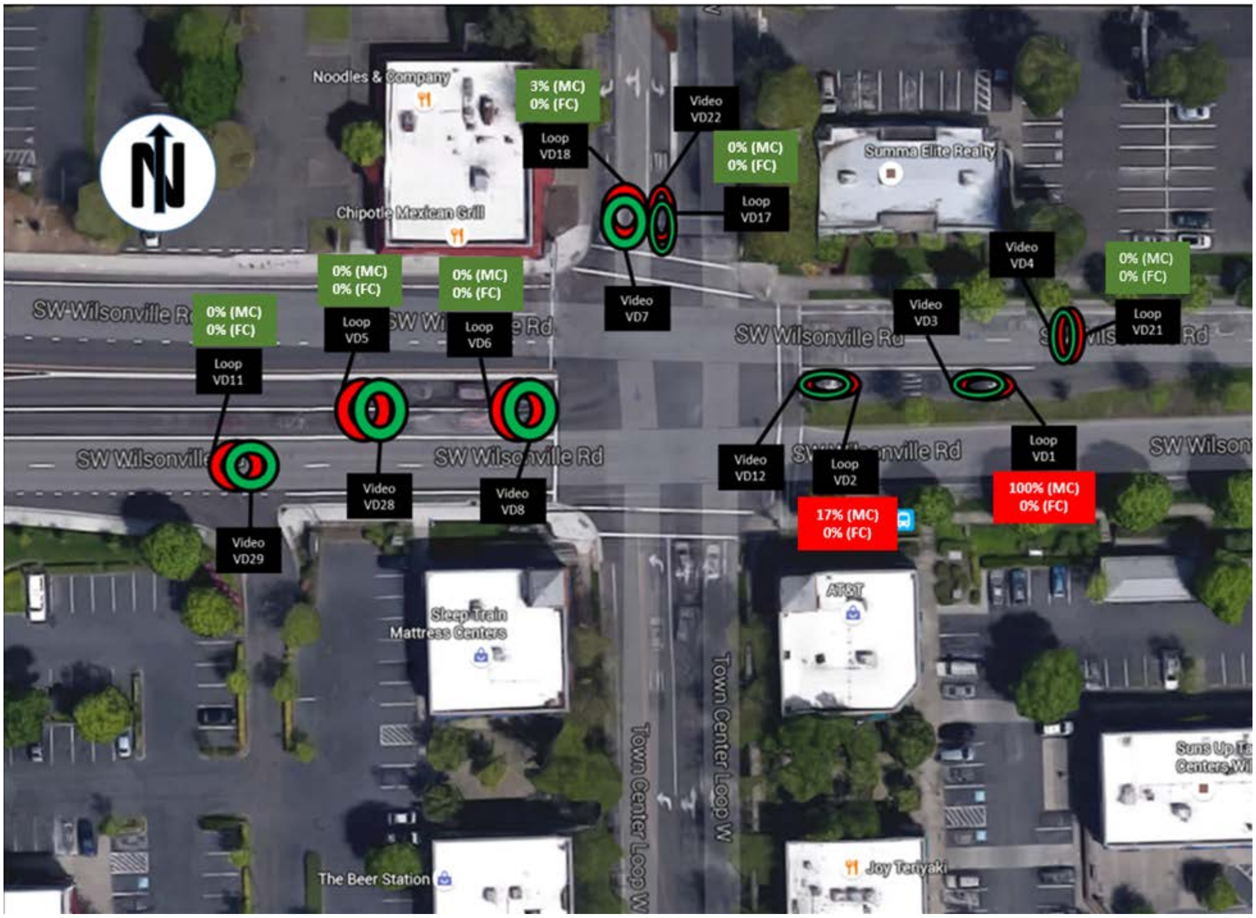


Figure 5.2: Graphic Representation of Ground Truth Results at SW Wilsonville Rd & Town Center Loop West

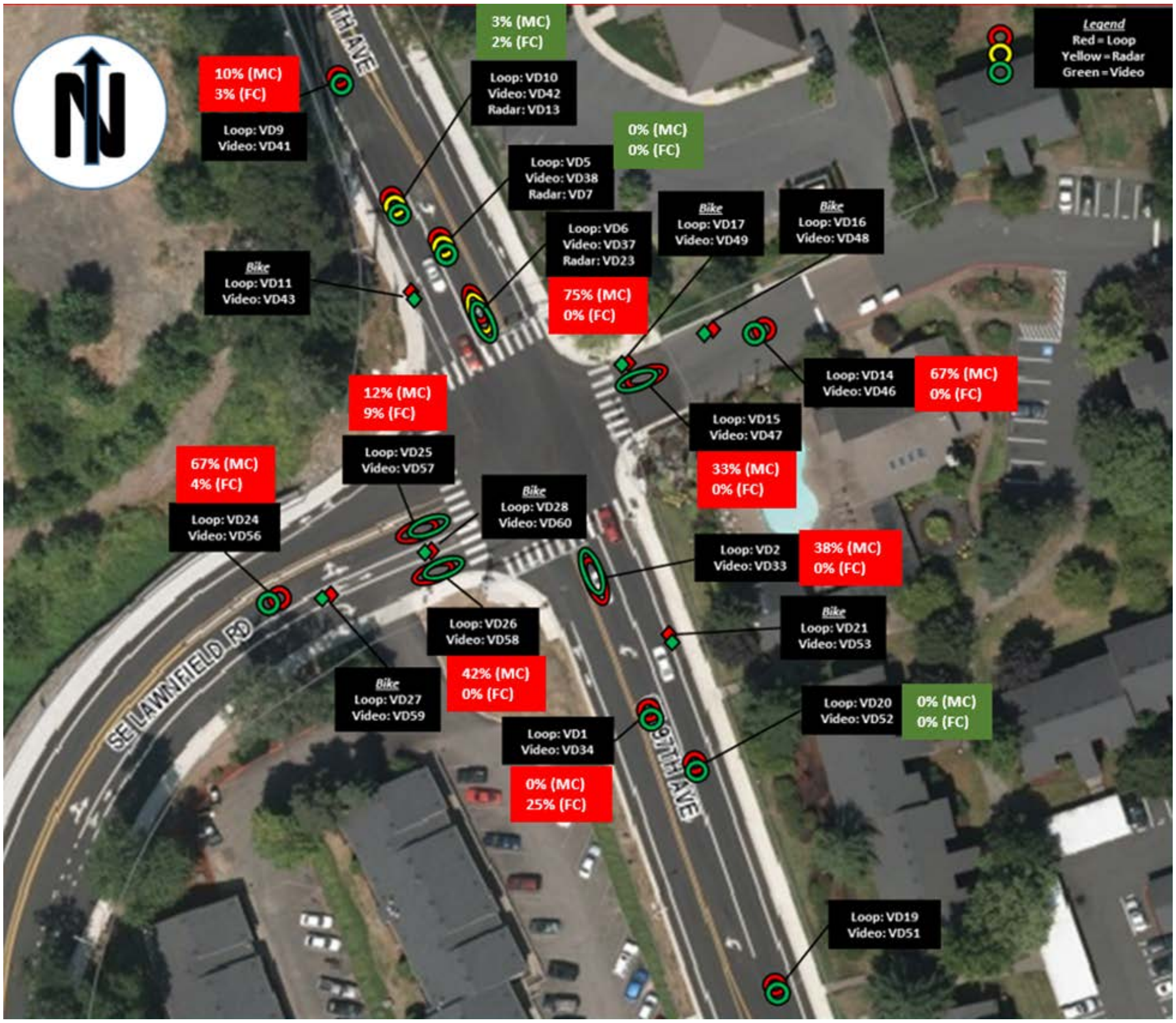


Figure 5.3: Graphic Representation of Ground Truth Results at 97th Avenue & SE Lawnfield Road

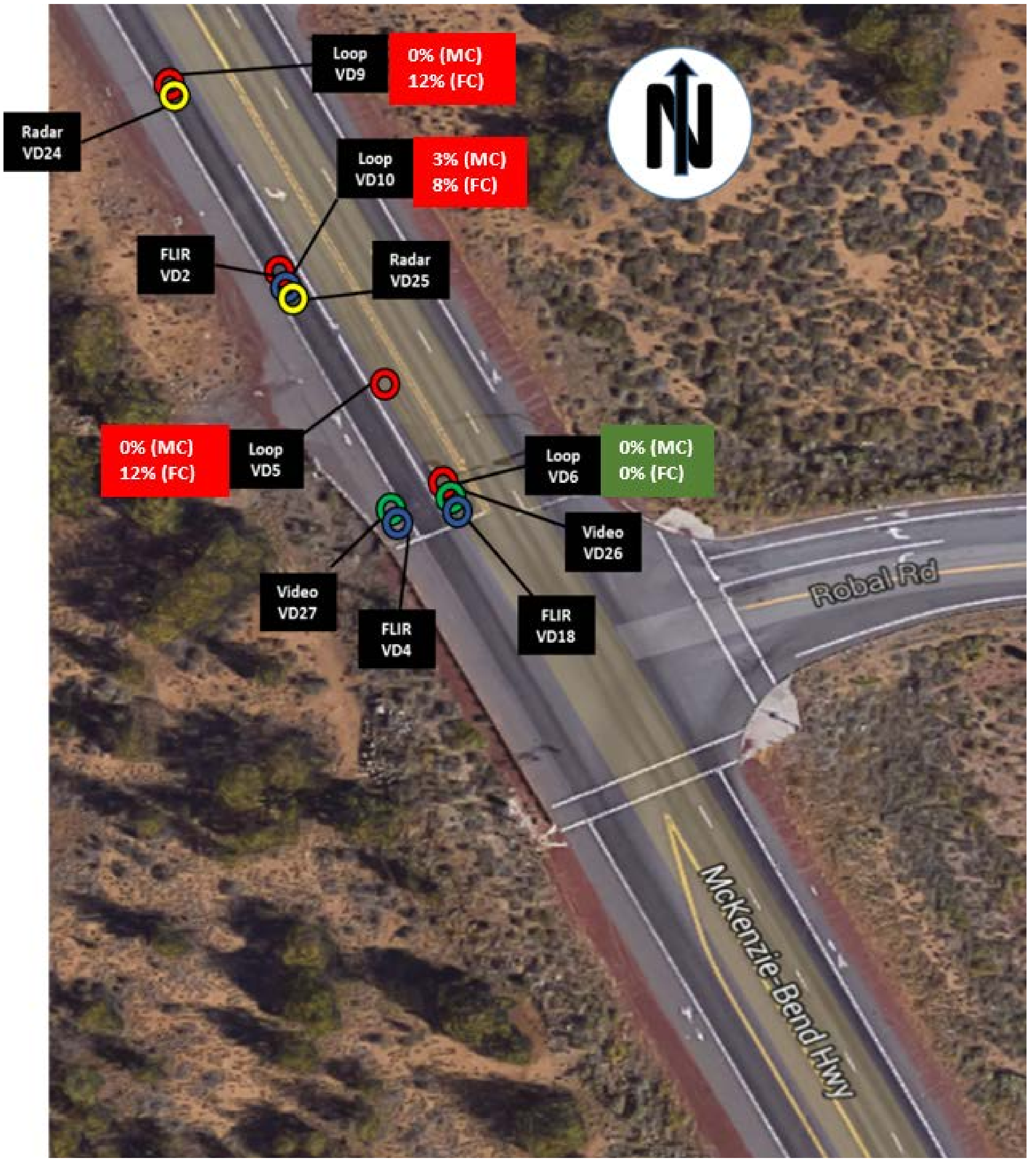


Figure 5.4: Graphic representation of ground truth results at US 20 & Robal Road

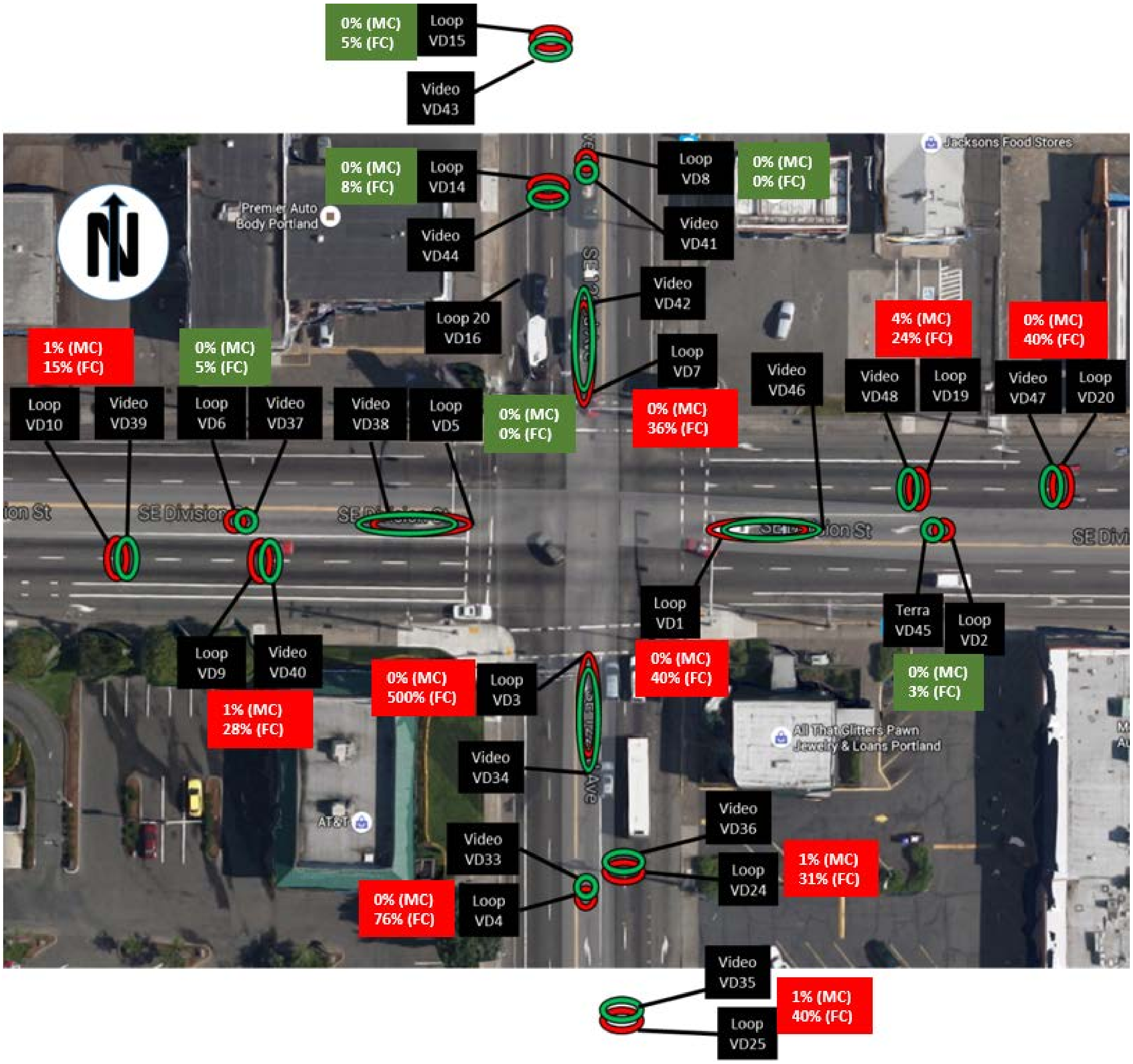


Figure 5.5: Graphic Representation of Ground Truth Results at SE 122nd Avenue & Division Street

5.2 DATA PROCESSING FOR ELIMINATING INVALID DATA

This study is designed to evaluate the performance of non-invasive sensors in normal weather and traffic conditions. Thus, in addition to the high-resolution sensor data, weather information during the data collection periods was collected from the weather stations closest to the data collection sites (Table 5.8). Weather information collected included visibility, precipitation, weather events (rain, overcast, etc.), among others.

Table 5.8: Weather Site Locations

Site	Location	Elevation (ft)	Latitude	Longitude
Wilsonville Rd & TCLW	**Wilsonville, OR**	**151**	**45.30 °N**	**122.77 °W**
US 20 & Robal Rd	**Bend, OR**	**3545**	**44.09 °N**	**121.31 °W**
97th Ave & Lawnfield Rd	**Clackamas, OR**	**866**	**45.44 °N**	**122.55 °W**
SE 122nd & SE Division St	**Portland, OR**	**259**	**45.50 °N**	**122.52 °W**

Table 5.9: Filtering criteria for data cleansing

No	Data Filtering Conditions	Details
1	Sensor setup error	SW Wilsonville Rd & Town Center Loop: 05/11/2016 – 05/18/2016
2	Video record failure	There is no video record, or video record image is not clear.
3	Low visibility	Visibility lower than 1 mile
4	Inclement weather	Weather events: rain, heavy rain, thunderstorm, light thunderstorms and rain, haze, mist, fog, and smoke
5	TraSER record failure	The status changes of sensors are from 0 to 0, or 1 to 1

Since the analysis only includes fair weather, all data collected under inclement weather or low visibility were eliminated. In addition to those, the data with either video record failure or software record failure were also excluded. Table 5.9 lists the filtering criteria used for eliminating invalid records. The specific data cleansing procedures at each site are further described below.

5.2.1 Sensor Setup Error

At SW Wilsonville Rd & Town Center Loop West, the original configuration for several of the video zones was not completed correctly. This was rectified shortly after data collection began, but because of this data from 05/11/2016 to 05/18/2016 was excluded from analysis.

5.2.2 Video Record Failure

During the data collection, occasionally video records were unavailable due to a number of reasons, including loss of video feed, software error, and Microsoft Windows' popups. This data is excluded from analysis, because the events that occurred cannot be verified, if necessary.

5.2.3 Low Visibility, Inclement Weather

Many research studies have noted that low visibility greatly influences traffic operation *(Hill and Boyle 2007, Kyte et al. 2001, Usman et al. 2010)*. In this study, visibility under 1 mile was designated as low visibility conditions. In addition, adverse weather conditions such as rain, heavy rain, thunderstorm, light thunderstorms and rain, haze, mist, fog, and smoke, are noted as inclement weather conditions. All the data collected under low visibility or inclement weather conditions are excluded from the data analysis. Table 5.9 lists the filtering criteria used to detect inclement weather. Across all records, 25.6 hours of data were excluded due to low visibility or inclement weather.

5.2.4 TraSER Record Error

Theoretically, the status change of sensors should always be from 1 to 0, or 0 to 1. That is, the sensor should be either from "ON" to "OFF", or vice versa. Occasionally, the status of sensors changed from 1 to 1, or 0 to 0. Typically, this occurred when TraSER was stopped and later restarted during the data collection period. Whenever this was encountered, it questions the validity of other records during that period. Therefore, the data collected during these time periods were excluded. During the data collection periods, the software record errors happened for 30 times over 19 day period, with a total duration time of about 11.9 hours. It is believed that these occurred concurrent with visits from field personnel to retrieve data from the Fit PC.

5.3 SUMMARY

This chapter discussed the preprocessing of the data which were cleaned from two aspects: First, each inductive loop zone was manually ground truthed for 15 minutes, with zones excluded if their error rate was above 10%. Second, the acceptable data from the ground truthing process were subjected to further cleansing, where further data were omitted due to sensor recalibration, inclement weather, data logging, and video recording errors.

6.0 ADVANCE SENSOR ANALYSIS

6.1 BACKGROUND

Advance sensors are primarily used for three functions in traffic signal control, namely collecting counts, estimating occupancy, and implementing gap-out logic. In adaptive control, advance sensors are used as system detectors to collect volume and occupancy information to drive the adaptive algorithm. In both adaptive and coordinated operation, they are used to provide dilemma zone protection. This report uses five-minute bins for activations and occupancy, and two-minute bins for time to gap out as measures for comparing non-invasive technologies to inductive loops.

Table 6.1 provides the details of these performance measures. It should be noted that activations were used as a surrogate for counts, as it was not feasible to record both presence and count outputs (if available) from all detection zones. The bin size of 5-minutes was selected for two reasons: insights gained using sensitivity analysis of different aggregation interval (Section 6.3) pointed to this as a reasonable interval, and similarity with the interval used by Northwest Signal's (NWS) Transcend product, which at the onset of the work was the adaptive product of focus. The time period of 2-minutes used for identification of gap was selected as it is a rough surrogate for an average cycle length.

Only loop sensors passing the reliability verification are used in the following analysis. There are a total of 11 advance loop sensors that passed the reliability verification, which correspond to 11 pairs of loop and video sensors and 2 pairs of loop and radar sensors, as listed in Table 6.2. These sensors are at SW Wilsonville Rd & Town Center Loop West, 97th Avenue & SE Lawnfield Road, and SE 122nd Avenue & Division Street.

In the column "sensor#" in Table 6.2 the 1st number refers to the loop sensor number and the 2nd number refers to the non-invasive sensor number. These correspond directly to the Voyage Detector numbers used in intersection control (I & J files). As such, there may be instances of the same Sensor # being present at different intersections.

Table 6.1: Advanced Detection Performance Metrics

	Advance Sensor		
Performance Measure	*5-min Activation*	*5-min Occupancy*	*Time to Gap-out (Gap >3.5 sec)*
Definition	Number of activations observed during 5 min period	Percentage of time the detector was occupied during 5 min period	Time to find the first gap greater than 3.5 sec during a 2-min interval
Use in Traffic Control	Used for assessing demand on the main street	Used for assessing demand on the main street	Used for implementing Dilemma Zone Protection

Table 6.2: Advance Sensors Passing the Ground Truth Verification

No	Intersection	Sensors #	Non-invasive sensors	Distance to stop bar (ft)	Location
1	SW Wilsonville Rd & Town Center Loop West	(5,28)	Video	75	LT
2		(11,29)	Video	110	TH/RT
3		(21,4)	Video	110	TH/RT
4	97th Avenue & SE Lawnfield Road	(5,38)	Video	75	LT
5		(5,7)	Radar	75	LT
6		(10,42)	Video	110	TH/RT
7		(10,13)	Radar	110	TH/RT
8		(20,52)	Video	110	TH/RT
9	SE 122nd Avenue & Division Street	(2,45)	Video	102	LT
10		(6,37)	Video	100	LT
11		(8,41)	Video	103	LT
12		(14,44)	Video	85	TH
13		(15,43)	Video	188	TH

Lastly, in general it should be noted that improved performance of all of the video detection metrics analyzed would likely improve if the non-invasive unit were mounted at the advance zone, rather than across the intersection, as was the case in this study.

6.2 REMOVAL OF VIDEO SENSORS BASED ON RAFFIC FLOW CHARACTERISTICS

This study focuses on comparing the performance of loop sensors and non-invasive sensors during normal operational conditions to provide implementation guidance. Figure 6.1 shows the relation between the loop occupancies and the differences of video occupancies and loop occupancies. The occupancies are aggregated based on 5-minute intervals with the X axis showing loop occupancy and the Y axis showing the difference of video occupancy and loop occupancy. When the differences are positive, highlighted by the green markers, the video occupancies are larger than the loop occupancies. When the differences are negative, highlighted by red markers, the video occupancies are smaller than the loop occupancies. When the differences are close to zero, the video occupancies are close to the loop occupancies. The sensor numbers are indicated on each respective plot. Figure 6.1 shows that the loop and video sensor pairs (6, 37), (8, 41), (15, 43), and (2, 45) have a significant number of negative occupancy difference values. That is, the video occupancies are less than the loop occupancies in nearly all the data, which contradicts the past literature and general expectancy. Rhodes et.al. *(Rhodes et al. 2006)* compared three technologies of video detection and showed that video on average picks up a vehicle earlier than a loop and drops the call later than the video. This suggests that occupancy for video should be in most cases higher than the loop detector. As such, any video sensor showing a reversal of this trend was further investigated by conducting additional ground truth. Under further exploration, all four pairs reporting this trend had a high number of missed or false calls (>10%) for either loop or video sensor and therefore were not included for statistical modeling. After eliminating sensors deemed to be unreliable due to ground truth and unexpected operation, seven pairs of loop and video sensors were available for statistical modeling. The final sensor list included for data driven statistical modeling is shown in Table 6.3.

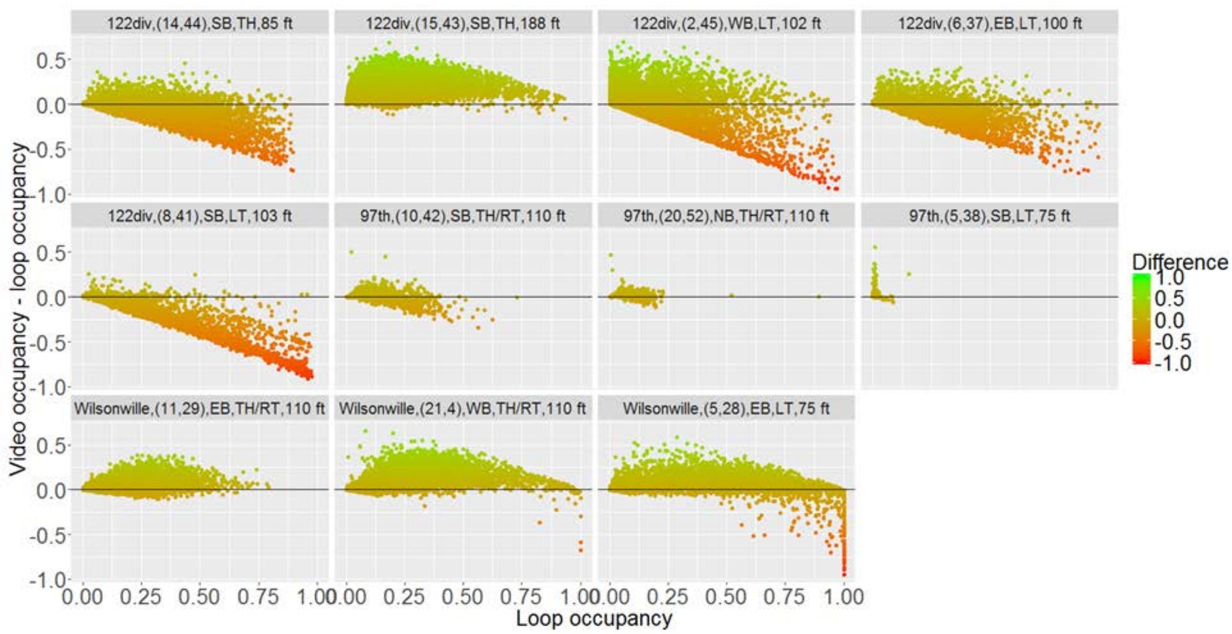


Figure 6.1: Loop Occupancy vs Occupancy Difference of Loop Sensors and Video Sensors

Table 6.3: Final Available Advance Sensors

No	Intersection	Sensors	Non-invasive sensors	Distance to stop bar (ft)	Location	Direction	Technology
1	SW Wilsonville Rd & Town Center Loop	(5,28)	Video	75	LT	EB	Solo pro
2		(11,29)	Video	110	TH/RT	EB	
3		(21,4)	Video	110	TH/RT	WB	
4	97th Avenue & SE Lawnfield Road	(5,38)	Video	75	LT	SB	On core
5		(5,7)	Radar	75	LT	SB	
6		(10,42)	Video	110	TH/RT	SB	
7		(10,13)	Radar	110	TH/RT	SB	
8		(20,52)	Video	110	TH/RT	NB	
9	SE 122nd Avenue & Division Street	(15,43)	Video	188	TH	SB	Terra

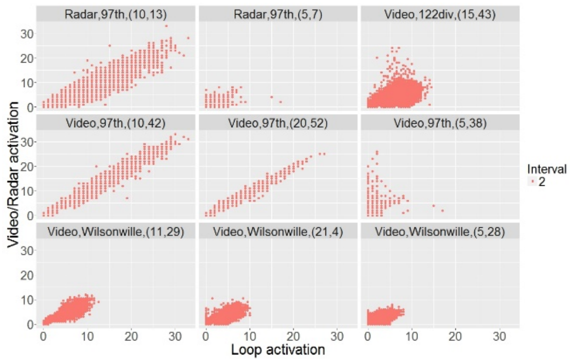
6.3 EFFECTS OF AGGREGATION TIME PERIOD

In order to better understand the impact of aggregation intervals on the data analysis, raw data were aggregated into bins of 2 minutes, 5 minutes, 10 minutes, and 15 minutes. Figure 6.2 and Figure 6.3 present scatter plots of loop activations vs. video/radar activations and loop occupancy vs. video/radar occupancy of each pair of sensors, respectively, for predefined intervals visualized separately under different levels of aggregation. The plots are also separated by sensor type. These scatter plots contain points from all sensors deemed to be valid.

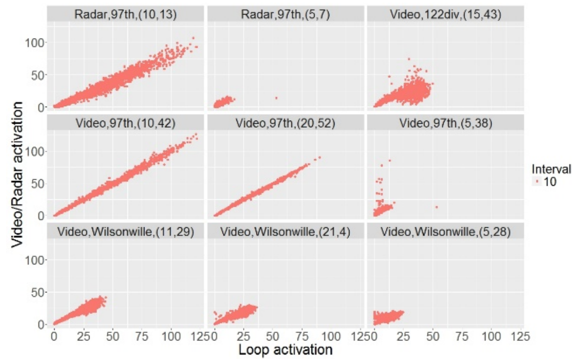
It can be seen that under different aggregation time periods, the activations and occupancies of loop sensors and non-invasive sensors show similar characteristics with a reduced spread. The trade-off between error variability and control responsiveness needs to be considered prior to choosing the aggregation interval. In this study, an aggregation interval of 5 minutes is used for technology comparison as that was the aggregation interval recommended by NWS Transcend, the adaptive control of focus at the onset of this research. In addition, given the technological differences of video sensors and radar sensors, they will be analyzed separately.

In Figure 6.2 and Figure 6.3, a straight line at 45 degrees emanating from the origin corresponds to a one to one correlation between loop activations and video activations. Activations of video and loop sensors at 97th Ave & SE Lawnfield Road and Wilsonville Rd & TCLW are mostly in sync with each other as shown by a significant number of the points lying along the 1:1 slope line whereas at SE 122nd & SE Division the pattern is more dispersed. Regarding occupancy, the overall trend shows a much greater spread (as shown in Figure 6.3) with video occupancy typically above the unit slope line, although the spread does appear to tighten somewhat with larger bin sizes. This implies that video occupancies are usually larger than the corresponding loop occupancies as was expected from prior work.

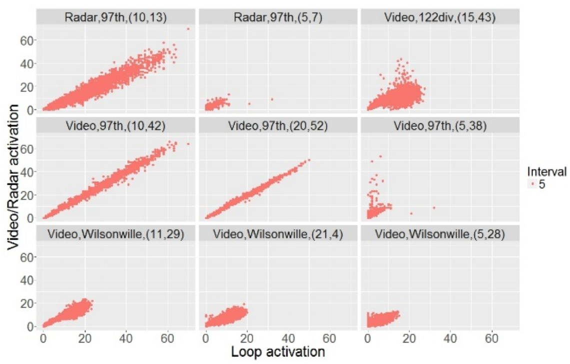
When comparing radar vs. loop, the technology at 97th appears to perform fairly consistently for both activation and occupancy while performance at the Bend site is less than ideal, with occupancy values deviating greatly from loop occupancies. It should be noted that number of radar zones is significantly lower than video zones (2 vs 7), thus resulting in lower observed variability in radar vs loop plots.



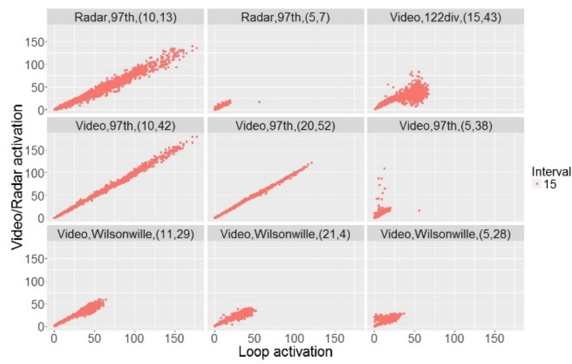
a) 2-minute bin



c) 10-minute bin

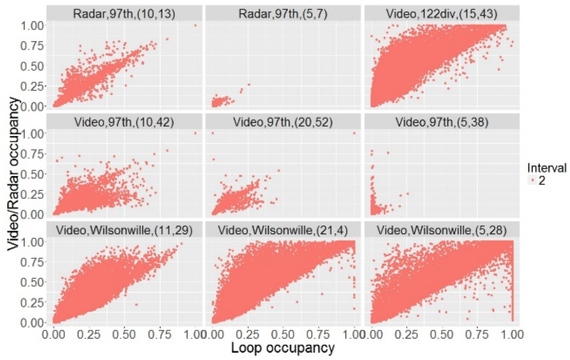


b) 5-minute bin

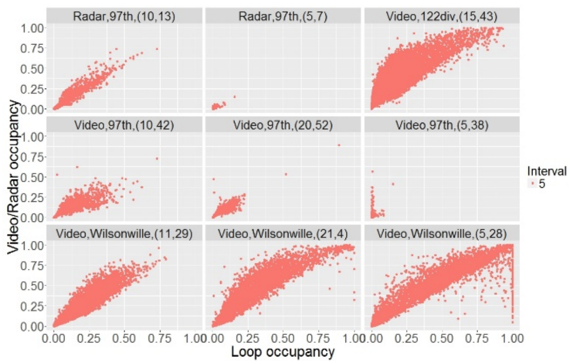


d) 15-minute bin

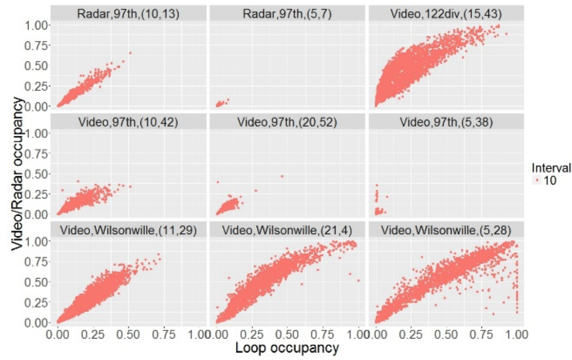
Figure 6.2: Loop activation vs video/radar activation aggregated by 2min, 5min, 10min, and 15min



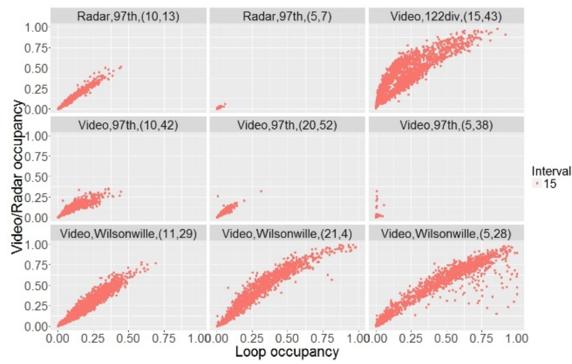
a) 2-minute bin



b) 5-minute bin



c) 10-minute bin



d) 15-minute bin

Figure 6.3: Loop occupancy vs video/radar occupancy aggregated by 2min, 5min, 10min, and 15min

6.4 ADVANCE VIDEO SENSOR ANALYSIS

The subsequent sections present statistical models developed for the three performance measures to gain insight into the quantitative impacts of different dependent variables on performance discrepancies.

6.4.1 Activation Differences

Figure 6.4 shows the plot of activation differences between video sensors and loop sensors (y-axis) plotted against loop activations (x-axis) for each 5 minute interval. Positive differences imply that the video activations were higher than loop activations for a given five-minute interval and negative differences imply lower video activations as compare to its loop pair. Figure 6.5 shows the histograms of the activation differences. Higher spread across the zero line suggests that the video activations had a larger difference from the loop activations. Table 6.4 gives the summary of activation differences of each pair of sensors. For a six by six detector, the activation is often used as a surrogate for traffic volume thus video and loop difference would imply that there will be differences in the volume reported by video as compared to a loop sensor.

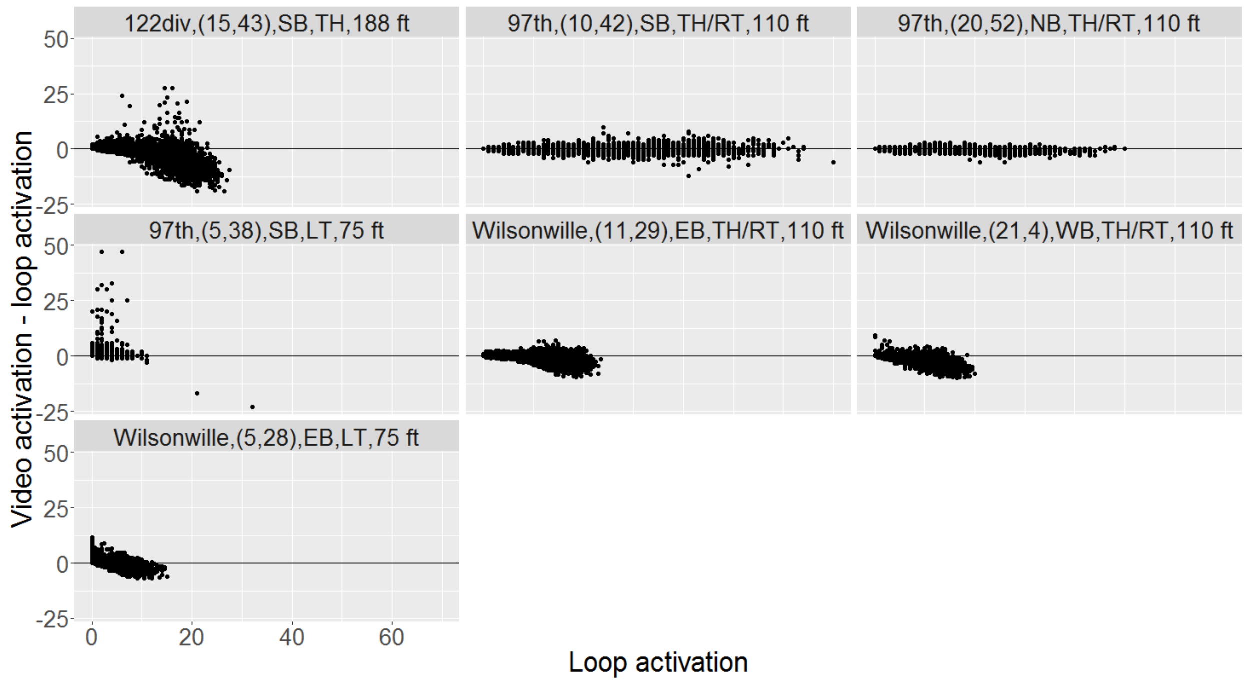


Figure 6.4: Activation Differences of Coupled Loop and Video Advance Sensors

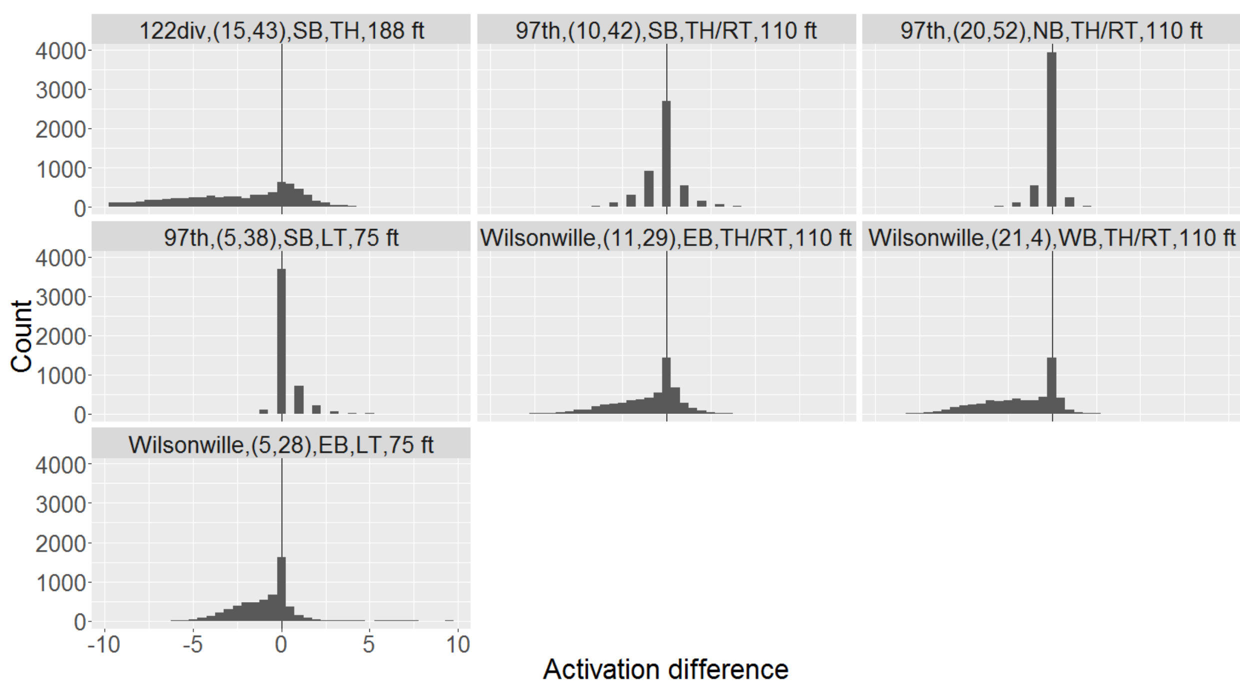


Figure 6.5: Histograms of Activation Differences of Coupled Loop and Video Advance Sensors

Table 6.4: Summary of Activation Difference of Advance Loop and Video Sensors

No	Intersection	Sensors	Mean	Median	5 percentile	95 percentile
1	SW Wilsonville Rd & Town Center Loop	(21,4)	-1.80	-1.5	-5.5	0.5
2		(5,28)	-0.87	-0.5	-4	1.5
3		(11,29)	-1.05	-0.5	-5	1.5
4	97th Avenue & SE Lawnfield Road	(5,38)	0.42	0	0	2
5		(10,42)	-0.16	0	-2	2
6		(20,52)	-0.11	0	-1	1
7	SE 122nd Avenue & Division Street	(15,43)	-2.73	-2	-10	2

Based on the activation difference, the data can be divided into two main types:

- Random differences: the activation differences fluctuate around zero difference, representing random error when compared to the loop sensor. The sensors at 97th Avenue & SE Lawnfield Road belong to this type. A t-test was completed to compare the loop activations and video activations for the sensors at the 97th Avenue & SE Lawnfield Road. The p-value of this test was 0.734, which indicates that the random difference is not significantly different from zero. As an example, 83.1% of total data of the sensors (20, 52) have zero activation difference.

- Systematic negative difference: the activation differences are mainly negative, representing a difference that is generally negative when compared to the loop sensor. The sensors at the SE 122nd Avenue & Division Street, and SW Wilsonville & Town Center Loop belong to this type. Again, a t-test was completed to compare the loop activations and video activations of these sensors. The p-value is smaller than 2.2e-16, which indicates that the activation difference is significantly different from zero. As an example, for the sensors (15, 43) at the 122nd Avenue & Division Street, 62.5% of the total data have the negative activation differences.

It was also seen that sensor pairs with systematic negative differences had a larger variance, implying that even if a bias correction were applied, there would still be high performance variability. The sites with lower variance and zero mean error will have better performance without changing any control parameters as set for an inductive loop detector. However, due to a limited number of experimental sites, it is difficult to statistically ascertain the factors responsible for random difference vs systematic negative difference. Some of the differences between sites include:

- All the videos cameras are mounted higher at 97th Avenue & SE Lawnfield Road as compared to other two intersections (mounting height is approximately double compared to other intersections)

- The detection technology used at 97th Avenue & SE Lawnfield Road is different from other two sites

- The 97th Avenue & SE Lawnfield Road site generally has lower occupancy values, implying that the queue rarely backs up to the advance detector.

Most existing models usually study the mean effects of covariates on response variables. For example, how would mounting height impact the output of a video sensor? In our case, the discrepancy range is of equal interest as it would provide an estimate of the expected deviation of performance from the loop sensor for a specified percent of time. This is important because many adaptive systems recommend inductive loops for various portions of their detection. For modeling discrepancy values, quantile regression models are commonly used. Quantile regression models the impact of covariates on user defined percentiles and thus can provide a measure of dispersion. Also, quantile regression is more robust against outliers in the response measurements than least squares regression. It is used to model conditional quantiles of response variables and their influencing factors. Quantile regression can provide more comprehensive information about the effects of covariates on the activation difference. Several studies in transportation have used this to estimate the dispersion in safety related measures *(Wu et al. 2013, Qin et al. 2010).*

The statistical models proposed for this study will model the 5th and 95th percentiles. Thus, the 5th and 95th percentiles will define the bounds that will contain difference for 90% of times, in line with the 10% error value used earlier for the sensor ground truth. Variables that are investigated for assessing their impact on these percentiles are summarized in Table 6.5.

Table 6.5: Summary of Variables Used in the Quantile Regression Model of the Activation Difference

Variable	Definition	Min	Max	Mean	Std.
Loop occupancy	The occupancy of loop sensors in every 5 minutes	0	1	0.13	0.194
Loop activation	The activations of loop sensors in every 5 minutes	0	72	9.89	9.79
Intersection	• 1, 97th Avenue & SE Lawnfield Road • 2, 122nd Avenue & Division Street • 3, SW Wilsonville Rd & Town Center Loop West	• 1, 50.1% • 2, 14.5% • 3, 35.3%			
Daytime	• 1, daytime, 7AM to 7PM • 0, night, 7PM to 7AM	• 1, 50% • 0, 50%			
Lane type	• 1, LT lane • 0, TH(TH/RT) lane	• 1, 31.8% • 0, 68.2%			
Distance to stop bar	The distance of sensors to stop bar: • 1, around 200ft • 0, around 100ft	• 1, 75.4% • 0, 24.6%			

Table 6.6 provides results for the quantile regression model for activation differences of advance video sensors.

Table 6.6: The Quantile Regression Model for the Activation Difference of Advance Video Sensors

	5 Quantile				95 Quantile			
Variable	**Value**	**Std. Error**	**t-value**	**Pr(>|t|)**	**Value**	**Std. Error**	**t-value**	**Pr(>|t|)**
(Intercept)	-0.679	0.027	-25.037	0.000*	1.007	0.005	200.718	0.000*
Loop occupancy	-21.148	1.127	-18.767	0.000*	-0.973	0.592	-1.643	0.100
Loop occupancy ^2	24.502	1.235	19.845	0.000*	24.749	4.811	5.144	0.000*
Intersection: 122div	0.506	0.072	7.045	0.000*	1.764	0.055	31.862	0.000*
Intersection: Wilsonville	-0.268	0.036	-7.477	0.000*	0.119	0.022	5.477	0.000*
Daytime	0.023	0.020	1.137	0.256	0.920	0.019	49.125	0.000*
Lane type - LT	0.656	0.028	23.407	0.000*	0.073	0.034	2.139	0.033*
Loop occupancy: 122div	-37.113	1.633	-22.732	0.000*	-13.371	1.340	-9.980	0.000*
Loop occupancy: Wilsonville	-1.235	1.139	-1.085	0.278	-6.263	0.637	-9.825	0.000*
Loop occupancy^2: 122div	30.991	2.918	10.620	0.000*	-11.075	5.045	-2.195	0.028*
Loop occupancy^2: Wilsonville	-3.538	1.279	-2.766	0.006*	-12.712	4.827	-2.634	0.008*

Note: * significant at 0.05 level.

The following paragraph discusses salient insights gained by reviewing the model coefficients.

- Congestion, as evidenced by higher occupancies, has a statistically significant non-linear effect on activation differences and the effect varies by site.

- Both the 122nd and Wilsonville sites were found to have statistically significant differences from the 97th site. The 122nd site has much higher variability among the three intersections that were studied. At this site, the 5th percentile has a larger positive discrepancy, implying a lower number of activations as compared to loop, while the 95th percentile has a larger positive value, implying a larger number of activations as compared to loop. This shows the confidence band of activation difference is much wider for 122nd implying more inconsistent performance at this site.

- Although the variables, daytime and left turn are found to be statistically significant in the model, the low value of their coefficients implies that they don't have a major impact in the outcome of the models.

Figure 6.6 plots the estimated quantile over field observations of activation differences of all the advance video sensors. The 5 quantile model and 95 quantile model are expected to cover at least 90% percent of all the data. In this case, the 5 quantile model and 95 quantile model cover 90.3% of total data, which generally means the quantile regression model is good.

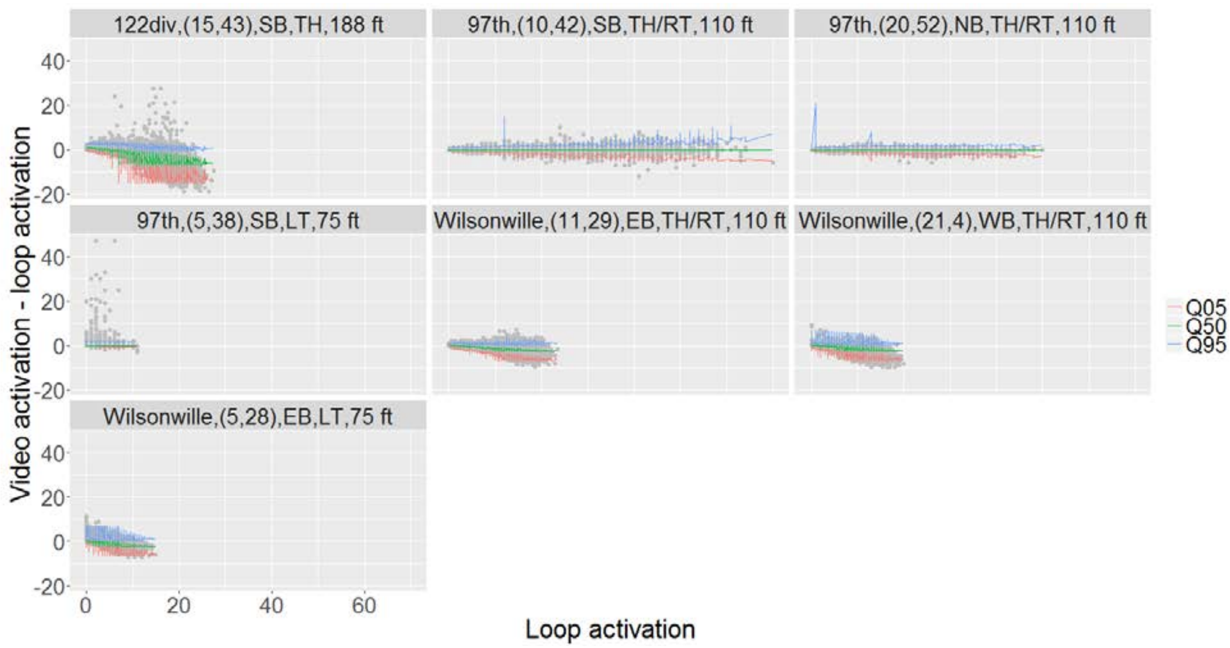


Figure 6.6: Estimated Quantile vs Field Observations of Activation Difference of Advance Video Sensors

Generally, it can be concluded that technology, location and other unobserved parameters can significantly impact activation differences. Since there are several factors that are different at the three sites, it is difficult to associate the observed activation differences to a single factor. Future work in this area might include additional sites to control for this heterogeneity and with that, more insight into the reason of differences in performance across the different sites might be learned.

6.4.2 Occupancy Difference

Occupancy is another input often used to estimate the demand, specifically when the queue from the intersection backs up to the detector resulting in the reported count being lower than the actual demand. Thus, it is critical to analyze the differences in occupancy reported by different sensor technologies. The occupancy difference of all the loop and video advance sensor pairs is shown in Figure 6.7. The x-axis represents the loop occupancy for a given 5-minute period and the y-axis represents difference between video occupancy and loop occupancy.

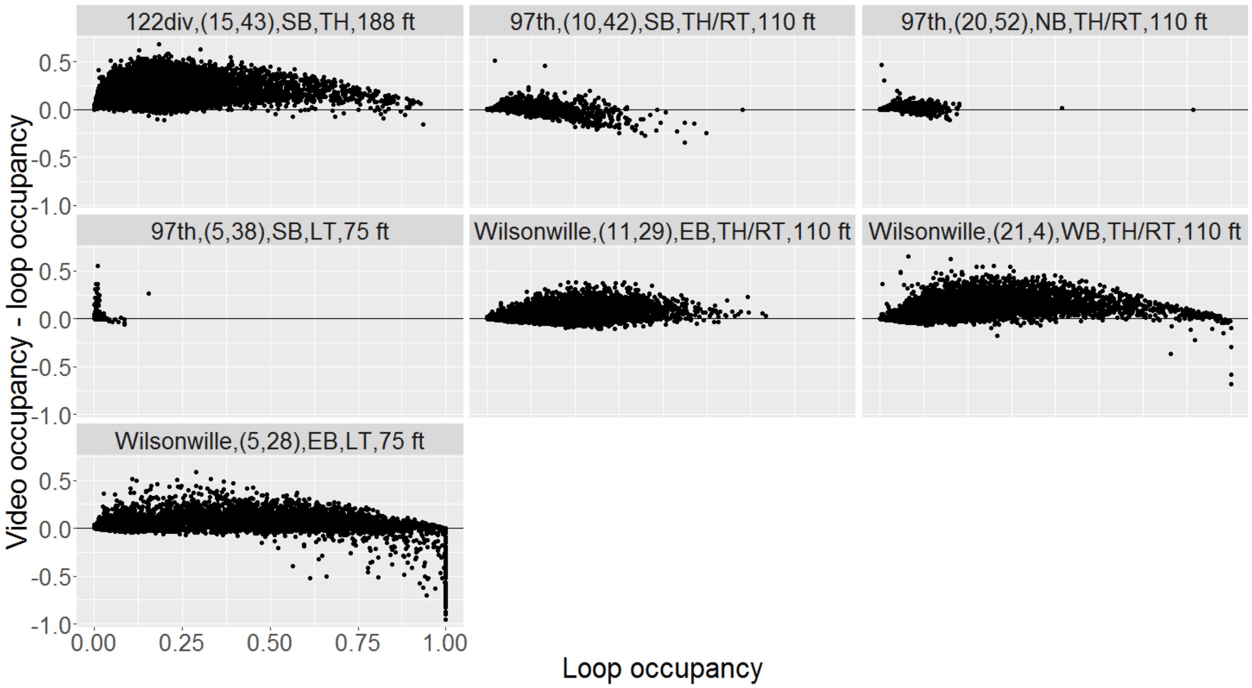


Figure 6.7: Occupancy Difference of Coupled Loop and Video Advance Sensors

The analyzed sensor pairs show that there is a near parabolic shape to the difference plots (several sensors with negative occupancy difference were excluded from analysis in Section **Error! Reference source not found.** after ground truth evaluation) with the occupancy difference peaking around 0.25 loop occupancy and then coming closer to 0 as the loop detector saturates. Figure 6.8 shows the histograms of the occupancy differences while Table 6.7 summarizes the occupancy differences. It should be noted that detector pair (5, 28) for the Wilsonville Eastbound Left shows anomalous behavior as loop occupancy approaches 1. Manual investigation of these points revealed that the loop sensor 5 was often stuck in “ON” status even though no vehicle existed, thus resulting in loop occupancy close to 1.

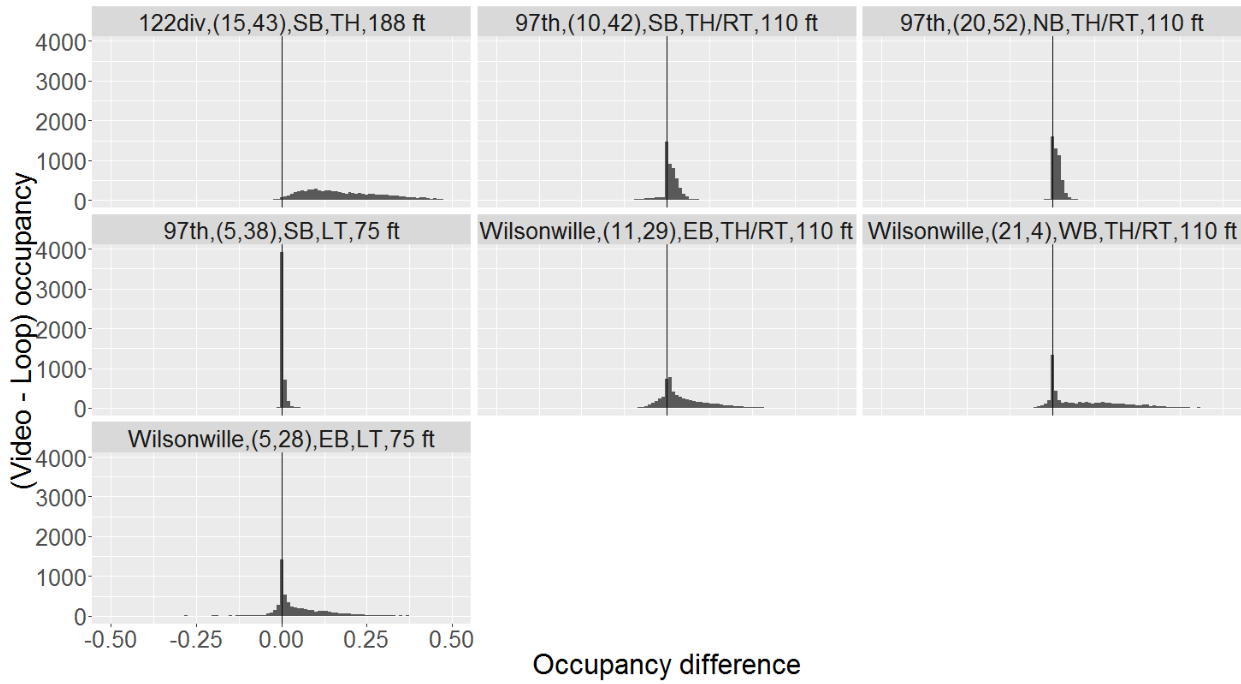


Figure 6.8: Histogram of the Occupancy Differences of Coupled Loop and Video Advance Sensors

Table 6.7: Summary of Occupancy Difference of Advance Loop and Video Sensors

No	Intersection	Sensors	Mean	Median	5 percentile	95 percentile
1	SW Wilsonville Rd & Town Center Loop	(21,4)	0.096	0.061	-0.013	0.310
2		(5,28)	0.042	0.017	-0.038	0.220
3		(11,29)	0.048	0.024	-0.037	0.197
4	97th Avenue & SE Lawnfield Road	(5,38)	0.004	0.001	0.000	0.016
5		(10,42)	0.011	0.009	-0.046	0.054
6		(20,52)	0.013	0.011	0.000	0.038
7	SE 122nd Avenue & Division Street	(15,43)	0.186	0.164	0.026	0.408

Figure 6.8 indicates that at the 97th Avenue & SE Lawnfield Road, most data fluctuate around zero. Table 6.7 further corroborates this, where the mean and the 90% percentile range of the occupancy differences at the 97th Avenue & SE Lawnfield Road are much smaller than other intersections. Also, for 97th Avenue & SE Lawnfield Road the loop occupancies are mostly below 0.5 showing that the queue didn't reach the advance sensor in most cases.

The following section explores the statistical significance of the covariates on the difference values and range using quantile regression. The same variables were used for this analysis were used for the quantile regression of activation difference, as presented in Table 6.5, with model results presented in Table 6.8.

Table 6.8: The Quantile Regression Model to the Occupancy Difference of Advance Video Sensors

	5 Quantile				95 Quantile			
Variables	**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**	**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**
(Intercept)	-0.0004	0.000	-5.355	0.000*	0.002	0.000	6.540	0.000*
Loop occupancy	0.035	0.023	1.504	0.132	0.817	0.042	19.344	0.000*
Loop occupancy ^2	-2.295	0.086	-26.705	0.000*	-1.149	0.342	-3.366	0.001*
Daytime	0.0004	0.000	2.491	0.013*	0.008	0.001	10.401	0.000*
Intersection: 122div	0.024	0.002	14.998	0.000*	0.279	0.004	67.181	0.000*
Intersection: Wilsonville	-0.027	0.001	-21.410	0.000*	0.020	0.003	6.728	0.000*
Lane type - LT	0.013	0.001	9.089	0.000*	0.000	0.004	0.068	0.946
Loop occupancy : 122div	1.013	0.034	29.948	0.000*	0.393	0.066	5.990	0.000*
Loop occupancy : Wilsonville	0.184	0.031	5.968	0.000*	0.419	0.049	8.514	0.000*
Loop occupancy ^2: 122div	1.072	0.093	11.490	0.000*	-0.428	0.349	-1.227	0.220
Loop occupancy ^2: Wilsonville	1.731	0.095	18.208	0.000*	-0.191	0.342	-0.558	0.577
Daytime: 122div	-0.176	0.004	-48.147	0.000*	-0.081	0.007	-11.332	0.000*
Daytime: Wilsonville	-0.027	0.002	-11.632	0.000*	0.032	0.006	5.419	0.000*

Note: * significant at 0.05 level.

Insight on the results of the quantile regression results for occupancy difference are listed below.

Loop occupancy: the loop occupancy shows significantly non-linear effects to the occupancy difference as the square of loop occupancy is found to be statistically significant in both models.

- Figure 6.9 shows the fitted occupancy difference values with the quantile regression mode for better understanding the impact of coefficients with varying loop occupancy. While initially, the occupancy difference increases with increase in loop occupancy, however it begins to decline as loop occupancy increases further. The lower occupancy implies that queue doesn't back up and cover the advance sensor. So under very low volumes, the video sensors overestimate the occupancy of some vehicles, and a large occupancy difference would be unexpected. When the loop occupancy is large, it means that vehicles have occupied the sensors for a long time and barring a major error in the video algorithm, the video occupancy would be one as well. Again, a large occupancy difference at this point would be unexpected as well. However, when the occupancies are in the medium range the differences seen are the highest. This might imply that video will be able to successfully detect oversaturated conditions but might struggle in medium volume conditions.

- The sensors at the122nd site have positive coefficients for both the 5th and 95th percentile coefficients. This implies that at the 122nd Avenue & Division Street, the occupancies measured by video typically have higher values with respect to the loop detector. Figure 6.9 also shows that the occupancy difference was relatively worse in low volume conditions as compared to other sites.

- Daytime and Left turn, although statistically significant, have very small coefficients. This implies that their impacts are only marginal on occupancies.

Figure 6.9 shows the estimated quantile and field observations of occupancy difference of all the advance video sensors. The fitted 5 quantile regression model and 95 quantile regression model cover 90.3% of the total data. Thus, the quantile regression model is generally good.

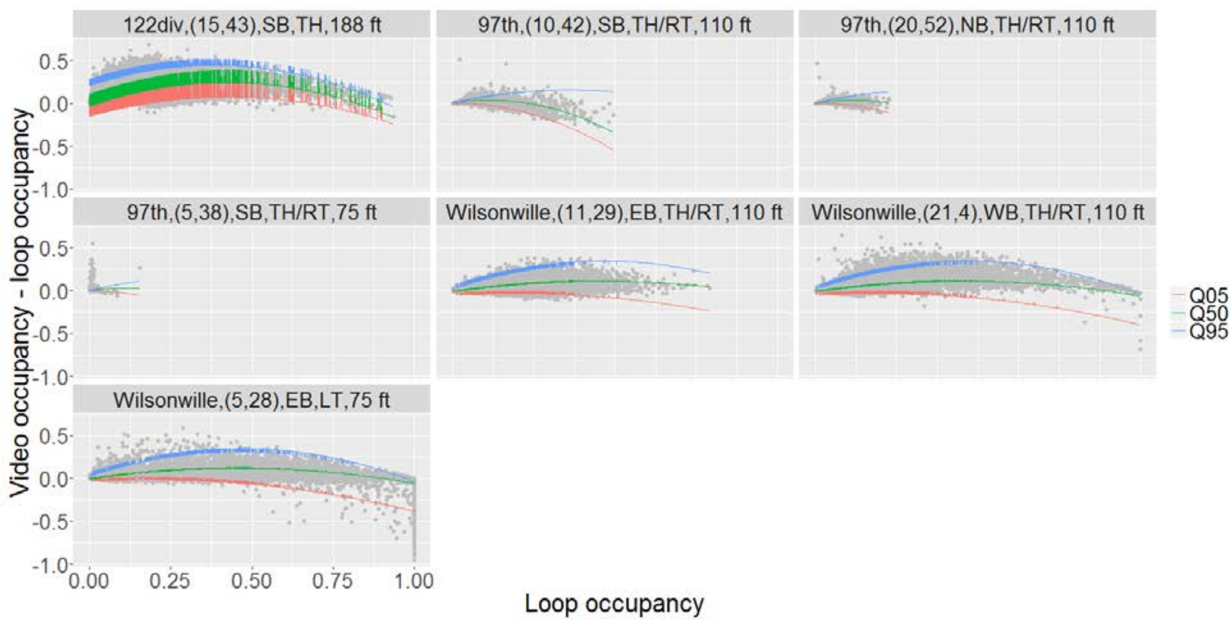


Figure 6.9: Fitted Occupancy Differences with the Quantile Regression Model of Advance Video Sensors

6.4.3 Time to Gap Out (TTG)

In both adaptive and non-adaptive control, advance detectors are often used for dilemma zone protection (DLZ). The Time to Gap-out surrogate is designed to assess the viability of replacing a loop sensor with a video sensor or other non-invasive technology. It should be noted that the replacement modeled here considers a replacement as a point detector. There are other vehicle tracking technologies which are non-invasive and have shown to provide improved dilemma zone protection as compared to inductive loops *(Sharma et al. 2011)* . Also, this work only focuses on through lanes to conduct this analysis as DLZ protection is only relevant to those lanes. There are 5 pairs of advance sensors available for this analysis, shown in Table 6.9.

Table 6.9: Available Coupled Loop and Video Advance Sensors for TTG Analysis

No	Intersection	Sensors	Distance to stop bar (ft)	Location	Direction	Technology
1	SW Wilsonville Rd & Town Center Loop West	(11,29)	110	TH/RT	EB	Solo pro
2		(21,4)	110	TH/RT	WB	
3	97th Avenue & SE Lawnfield Road	(10,42)	110	TH/RT	SB	On core
4		(20,52)	110	TH/RT	NB	
5	SE 122nd Avenue & Division Street	(15,43)	188	TH	NB	Terra

For this work, gap out time is set as 3.5s, a typically used extension value for providing dilemma zone protection (it is noted that this value is site and speed dependent in application). Any gap equal to or greater than 3.5s during each successive 2-minute interval is eligible to activate the gap out operation. The time to gap out is defined as from the starting time of every 2 minutes to the end of 1st available eligible 3.5s gap. For example, from 15:00:00 to 15:02:00 on 10/20/2015, sensor 15 at the SE 122nd Avenue & Division Street intersection detected an eligible gap which started at 15:00:08:538 and ended at 15:00:34:947. Thus, the TTG is 8.538+3.5=12.038s. When no eligible gap is found within the bin, TTG is set as 120s. When the 1st eligible gap starts at the beginning of a 2-minute bin, TTG is set as 3.5s.

Based on whether the sensors find available 3.5s gaps, all the data can be classified into four types:

- $L_{\text{g1}}V_{\text{g1}}$, both the sensors find an available gap
- $L_{\text{g1}}V_{\text{g0}}$, the loop sensor finds an available gap, but not the video sensor. In these cases, the video sensors do not allow the signal to gap out in time
- $L_{\text{g0}}V_{\text{g1}}$, the loop sensor does not find an available gap, but the video sensor finds one. In these cases, the video sensors would make the signal gap out when vehicles exist
- $L_{\text{g0}}V_{\text{g0}}$, neither of the sensors find an available gap.

Generally speaking, when using a video sensor instead of a loop sensor is considered, $L_{\text{g1}}V_{\text{g1}}$ and $L_{\text{g0}}V_{\text{g0}}$ data are desired and $L_{\text{g1}}V_{\text{g0}}$ and $L_{\text{g0}}V_{\text{g1}}$ data are not desired. Table 6.10 shows the compositions of TTGs.

Table 6.10: TTG Compositions of Coupled Loop and Video Advance Sensors

No	Intersection	Sensors	$L_{g1}V_{g1}$	$L_{g1}V_{g0}$	$L_{g0}V_{g1}$	$L_{g0}V_{g0}$
1	SW Wilsonville Rd & Town Center Loop	(11,29)	99.8%	0.1%	0%	0.1%
2		(21,4)	96.2%	2.0%	0.4%	1.3%
3	97th Avenue & SE Lawnfield Road	(10,42)	100%	0%	0%	0%
4		(20,52)	100%	0%	0%	0%
5	SE 122nd Avenue & Division Street	(15,43)	97.4%	2.1%	0.1%	0.4%

The 5 pairs of sensors have available gaps in nearly all the time intervals. Only the sensors (21, 4) at the Wilsonville Rd & Town Center Loop West, and the sensors (15, 43) at the 122nd Avenue & Division Street, have a few $\mathrm{L_{g1}V_{g0}}$ and $L_{g0}V_{g0}$ data. Considering the video sensors tend to have larger occupancies than loop sensors, this is understandable.

Since most data belong to the $L_{g1}V_{g1}$ data, they are the focus of analysis. Figure 6.10 shows the scatterplot of loop TTGs and video TTGs of all the $L_{g1}V_{g1}$ data, and Figure 6.11 shows the histogram of the ratio of video TTGs to loop TTGs. The histogram shows that most data lies close to 0.75-1.25 range. Figure 6.12 shows the scatterplot of the loop TTGs and video TTGs of the $L_{g1}V_{g1}$ data of each pair of sensors.

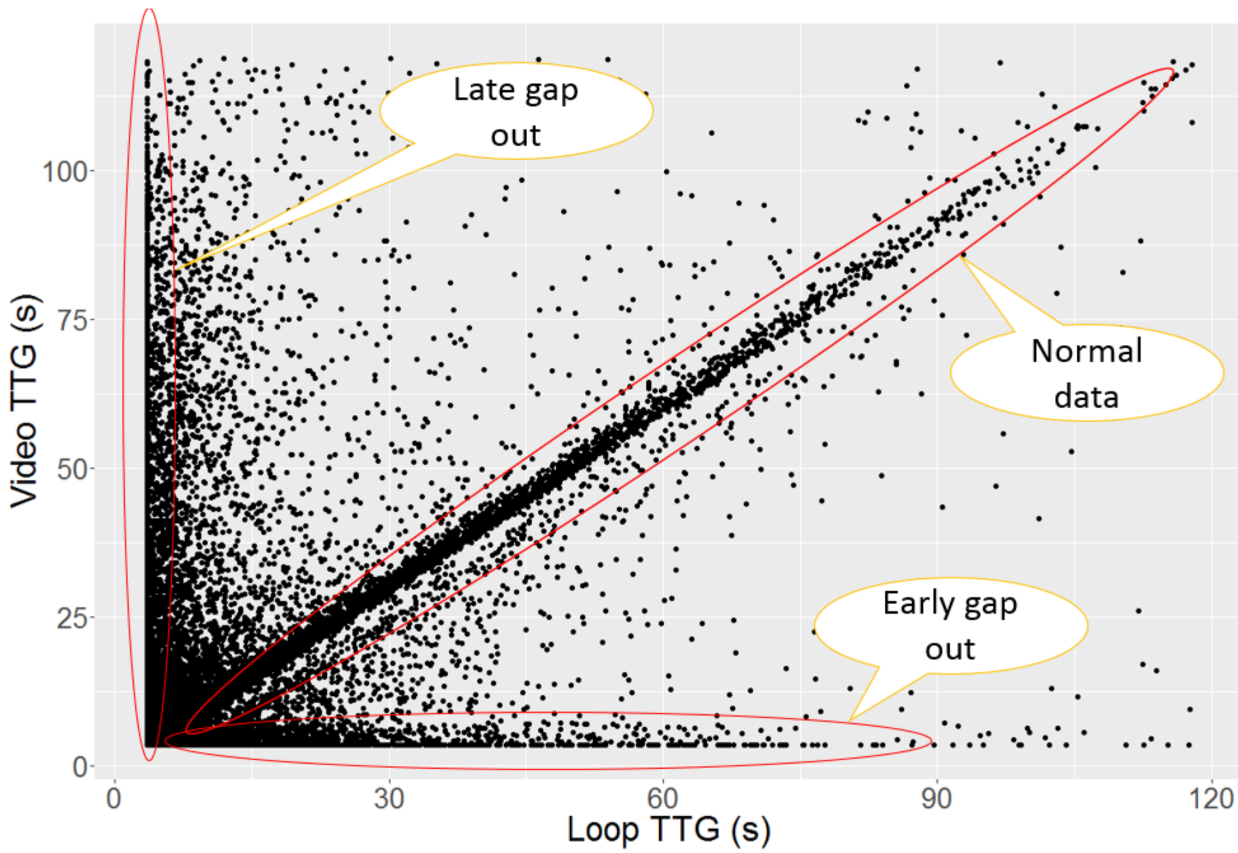


Figure 6.10: Loop TTGs vs Video TTGs of All the Coupled Advance Sensors

Three regions are immediately evident in the Figure 6.10. The middle region, termed ‘normal data,’ corresponds to the ideal condition where the loop TTG and video TTG are similar in values. For this data, the slope of the region is near 1. The data with the ratio of video TTGs to loop TTGs being 0.75 and 1.25, are classified as the ‘normal’ scenario with 80.1% of total data falling within this range.

The second region with slope nearly zero, annotated as ‘early gap out’ (EGO), shows that for certain two minute periods the video TTG was close to zero and loop TTG had a much higher value. In this region video would gap-out much earlier than when loop would have gapped out. EGO data occupy 5.5% of total data. The third region with slope much greater than 1, annotated by ‘late gap out’ (LGO), corresponds to the times where the loop gaps out nearly immediately but video takes a longer time to gap out. LGO data occupy 14.4% of total data.

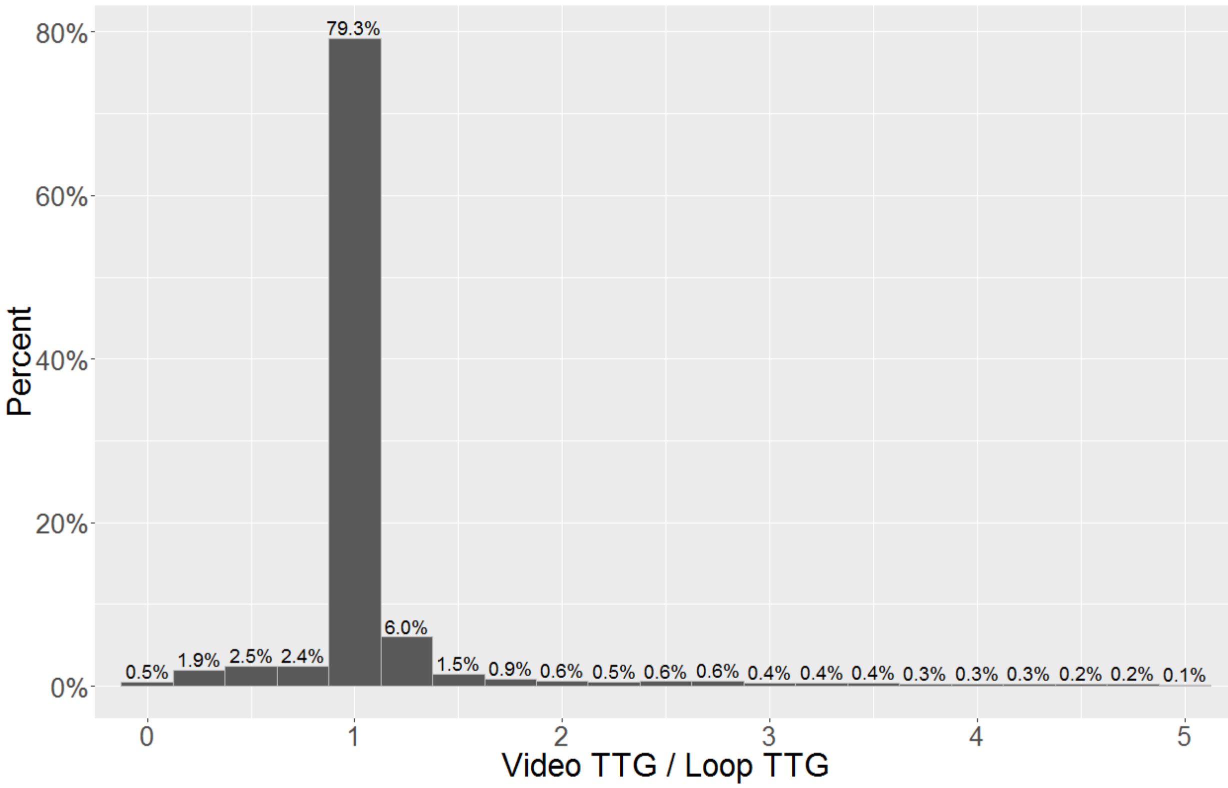


Figure 6.11:Histogram of the Ratio of Loop TTGs to Video TTGs

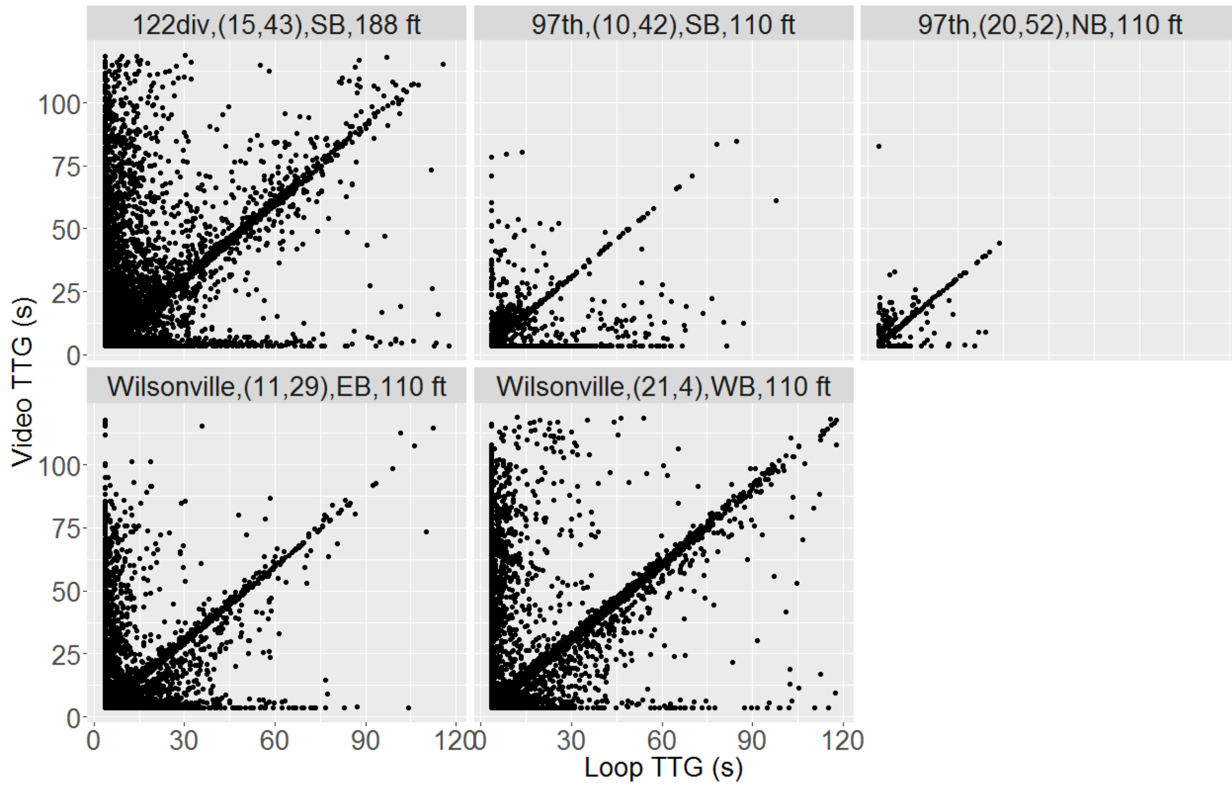


Figure 6.12: Loop TTGs and Video TTGs of Each Pair of Advance Sensors

Figure 6.12 shows that the two sensors at the 97th Avenue & SE Lawnfield Road have the best performance in TTG measure because most of the data are dispersed around the unit slope line. Higher EGO and LGO errors are observed at other sites.

Additionally, it should be noted that around 60% of time both loop and video gap out at the beginning of the two-minute interval, and that this is expected during off-peak and night time conditions. Around 27.2% of time, the loop TTG and video TTG is between initial gap out and max-out. This portion of the data set is used to compare the differences between loop and video performance for this metric. Statistical models were developed to find the statistically significant variables that impact the proportion of EGO and LGO present for a specific detector pair. In this case, since the data are classified into three types, it is thought that the influences of covariates on each type of data may vary greatly. The multinomial logistic model (MNL) is often used to identify the influencing factors when the categorical response variables have more than 2 levels. Thus, it is used here to identify the effects of covariates on the three types of data. The same variables as presented in Table 6.5 were used for the analysis. Only the variables showing statistically significant influences are retained in the final model. The results are shown in Table 6.11. The normal data is taken as the base case in the MNL model, the relative risk ratio signifies the relative probability of data being EGO/LGO data as compared to being in normal set.

Table 6.11: The Result of Multinomial Logistic Regression Model of TTGs of Advance Sensors

	EGO				LGO			
Variable	**Estimate**	**Std. Errors**	**P-value**	**Relative risk ratio**	**Estimate**	**Std. Errors**	**P-value**	**Relative risk ratio**
(Intercept)	-5.494	0.076	<2e-16*	0.004	-5.271	0.063	<2e-16*	0.005
Loop activation	0.199	0.005	<2e-16*	1.220	0.176	0.004	<2e-16*	1.193
Loop occupancy	1.718	0.092	<2e-16*	5.573	1.591	0.064	<2e-16*	4.906
Intersection – 122div	1.700	0.067	<2e-16*	5.474	3.325	0.054	<2e-16*	27.804
Intersection - Wilsonville	1.977	0.068	<2e-16*	7.218	2.632	0.058	<2e-16*	13.896
Residual Deviance: 83336.59. AIC: 83356.59								

Note: * significant at 0.05 level.

The salient insights as obtained from the MNL model are listed below:

- *Loop Activation:* for both the EGO and LGO data, the loop activation shows significant positive effects. The relative risk ratios of loop activation are 1.220 and 1.193 for EGO and LGO data, respectively. This means that when the loop activation value increases 1 unit, the TTGs are 22% more likely to be EGO data, and 19.3% more likely to be LGO data. That is, with the increase of loop activations, the likelihood of obtaining EGO and LGO increases.

- *Loop Occupancy*: for both the EGO and LGO data, the loop occupancy shows significant positive effects too. The relative risk ratios of loop occupancy for EGO and LGO data are 5.573 and 4.906, respectively. This means when the loop occupancy increases by 0.1, the data are 457.3% more likely to be the EGO data, and 390.6% more likely to be the LGO data. That is, with the increase of loop occupancy, the data are also more likely to be not the normal data. This implies queuing over the advance detector increases the error by a big margin.

- Compared with the 97th Avenue & SE Lawnfield Road, the data at the SE 122nd Avenue & Division Street are 547.4% and 2780.4% more likely to be EGO and LGO data, respectively. Similarly, compared with the 97th Avenue & SE Lawnfield Road, the data at SW Wilsonville Rd & Town Center Loop are 721.8% and 1389.6% more likely to be the EGO and LGO data, respectively. That is, the TTG at the 97th Avenue & SE Lawnfield Road are more likely to be normal data, where the video TTGs may be used to infer the loop TTGs. The finding is consistent with Figure 6.12.

6.5 RADAR SENSOR ANALYSIS

Two pairs of loop and radar sensors are available for analysis, (5,7) and (10,13), which are located at 97th Avenue & SE Lawnfield Road. Since video sensors were also available at the two locations, two detection zone triplets are formed for additional comparison, (5,7,38) for the left turn and (10,13,42) for the through movement.

6.5.1 Activation Difference

The activation differences of coupled loop and radar sensors are shown in Figure 6.13. To compare these differences against the video sensor differences, the activation differences of coupled loop and video sensors at the same locations are also shown in the figure. A stark difference in performance is observed between the pair (10,13) and (10,42). Radar consistently underestimates the number of activations while the video at the same location does perform consistently with a moderate amount of random error. For the triplet (5,7,38), not much difference is seen, which may be attributed to the low number of activations. Compared with the radar sensors, the video sensor tends to overestimate the activations at this location. There is a need to conduct future research with more sites where these three technologies are co-located to see if there is a wider transferability of this result.

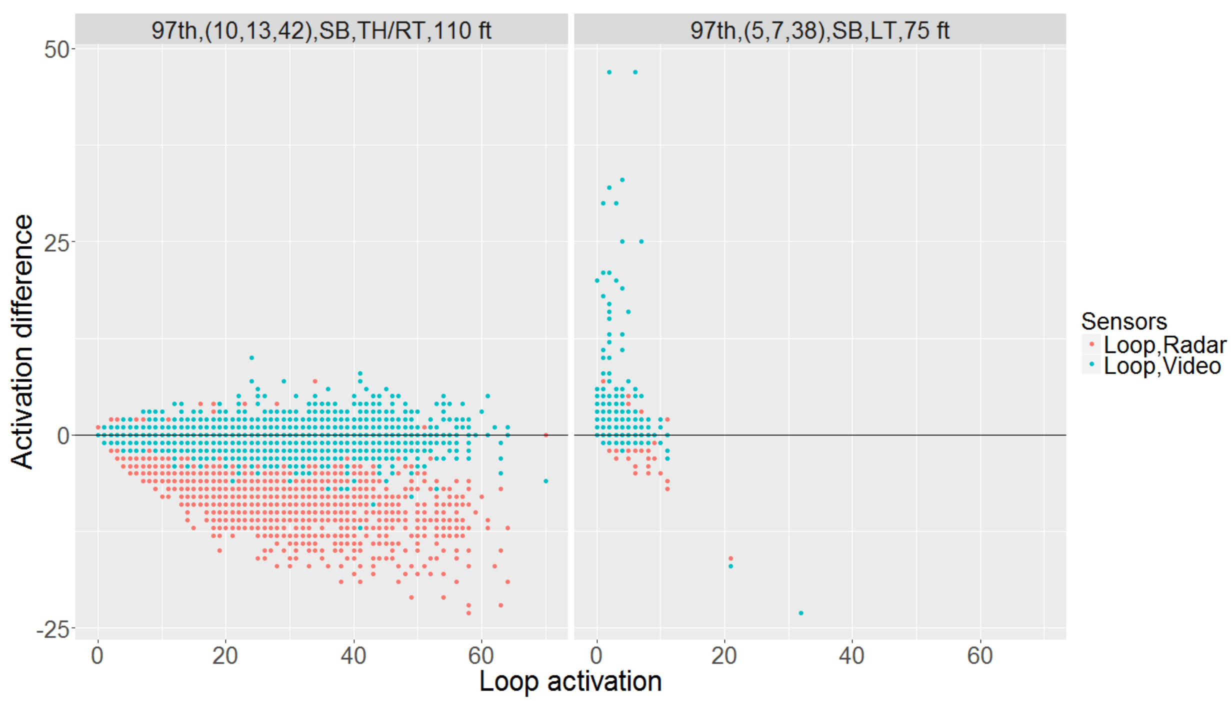


Figure 6.13: Activation Difference of Radar and Loop Sensors and Activation Difference of Video and Loop sensors

A quantile regression model with the activation difference of radar sensors and loop sensors as the response variable was built to identify any possible influential factors of the activation difference. The model result is shown in Table 6.12.

Table 6.12: Quantile Regression Model of the Activation Differences of Advance Radar Sensors

	5 Quantile				95 Quantile			
Variables	**Value**	**Std. Error**	**t-value**	**Pr(>|t|)**	**Value**	**Std. Error**	**t-value**	**Pr(>|t|)**
(Intercept)	0.000	0.032	0.000	1.000	1.072	0.013	80.650	0.000
Loop activation	-0.573	0.014	-40.961	0.000*	-0.034	0.013	-2.678	0.007*
Loop activation^2	0.005	0.000	15.279	0.000*	-0.001	0.000	-3.259	0.001*

Note: * significant at 0.05 level.

In both models, the loop activation is found to have significantly non-linear effects on the activation difference. In the 5 quantile model, with the increase of the loop activation, the radar sensors mainly tend to underestimate the traffic volume first, and then overestimate the traffic volume. However, in the 95 quantile model, with the increase of the loop activation, the radar sensors tend to overestimate the traffic volume first and then underestimate the traffic volume.

The fitted values with the quantile regression model are shown in Figure 6.14. The fitted values cover 90.3% of total data.

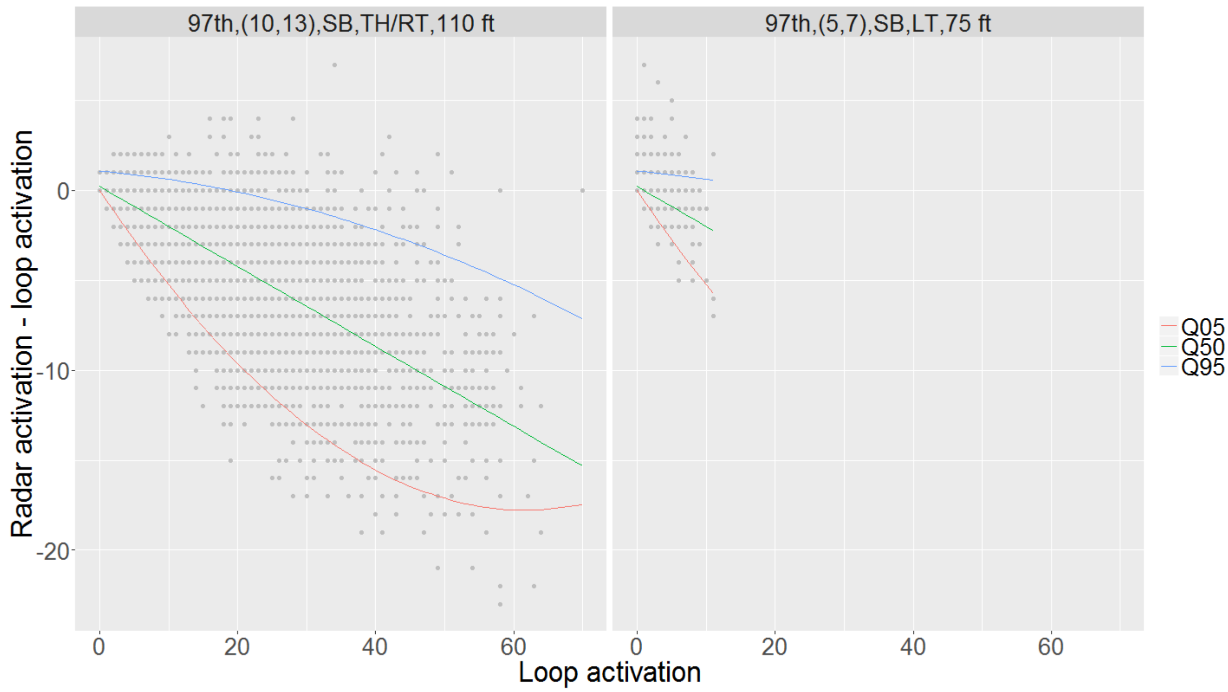


Figure 6.14: Fitted Activation Differences with the Quantile Regression Model of Advance Radar Sensors

6.5.2 Occupancy Difference

The scatter plot of occupancy differences vs loop occupancy for both the loop and radar sensor pair and loop and video sensor pair at the same location are shown in Figure 6.15, similar to **Error! Reference source not found.**. There are not many observations for the (5,7,38) triplet due to low volume at that approach, so it is hard to draw any transferable conclusions. For the sensor triplet (10,13,42), the occupancy differences of radar and loop sensors are mostly positive, meaning that the radar occupancy is usually larger than the loop occupancy. As loop occupancy increases, the occupancy difference between radar and loop seems to increase first and then decrease. Conversely, the occupancy differences of video and loop sensors have both negative and positive values.

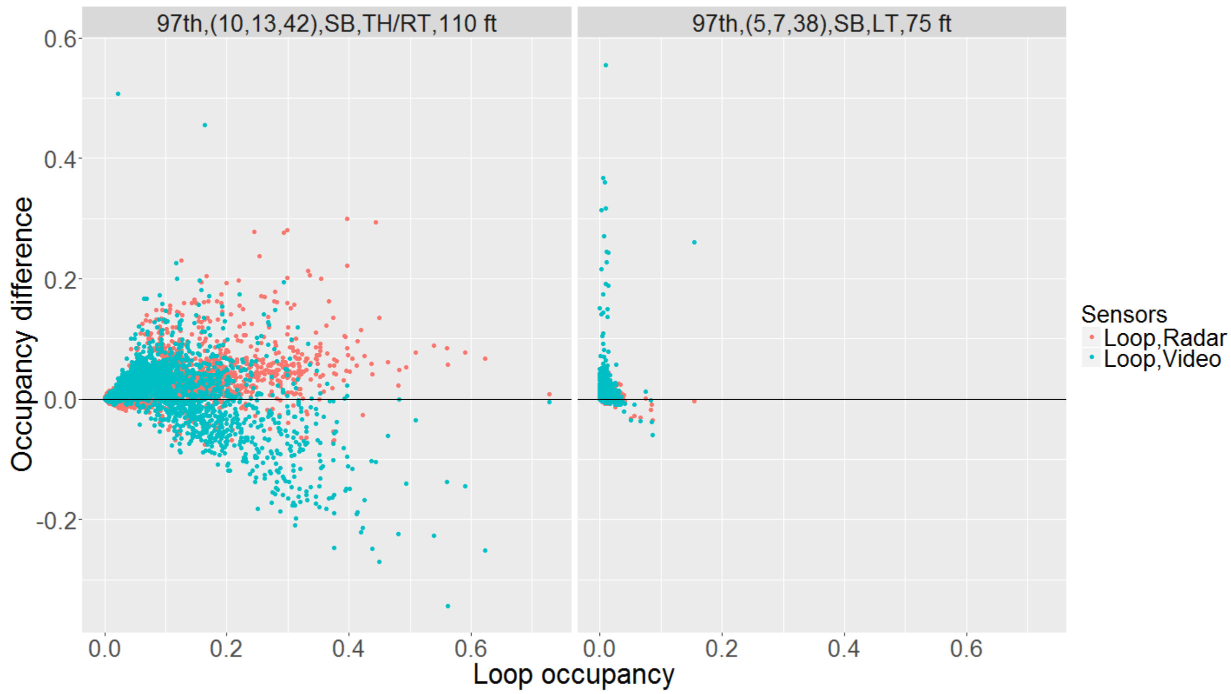


Figure 6.15 Occupancy Difference of Radar and Loop Sensors and Occupancy Difference of Video and Loop Sensors

A quantile regression model with the occupancy difference of radar sensors and loop sensors as the response variable was built to identify any possible influential factors of the occupancy difference. The model result is shown in Table 6.13.

Table 6.13: Quantile Regression Model of Occupancy Differences of Advance Radar Sensors

	5 Quantile				95 Quantile			
Variables	**Value**	**Std. Error**	**t-value**	**Pr(>|t|)**	**Value**	**Std. Error**	**t-value**	**Pr(>|t|)**
(Intercept)	-0.001	0.000	-11.074	0.000*	0.002	0.000	24.237	0.000*
Loop occupancy	-0.106	0.017	-6.331	0.000*	0.811	0.030	27.467	0.000*
Loop occupancy^2	0.163	0.079	2.054	0.040*	-0.609	0.112	-5.440	0.000*

Note: * significant at 0.05 level.

In both models, the loop activation is found to have significantly non-linear effects on the activation difference. In the 5 quantile model, with the increase of the loop activation, the radar sensor mainly tends to underestimate the occupancy first, and then overestimate the occupancy. However, in the 95 quantile model, with the increase of the loop activation, the radar sensors tend to overestimate the occupancy first and then underestimate the occupancy.

The fitted values with the quantile regression model are shown in **Error! Reference source not found.**. The fitted values cover 90.0% of total data.

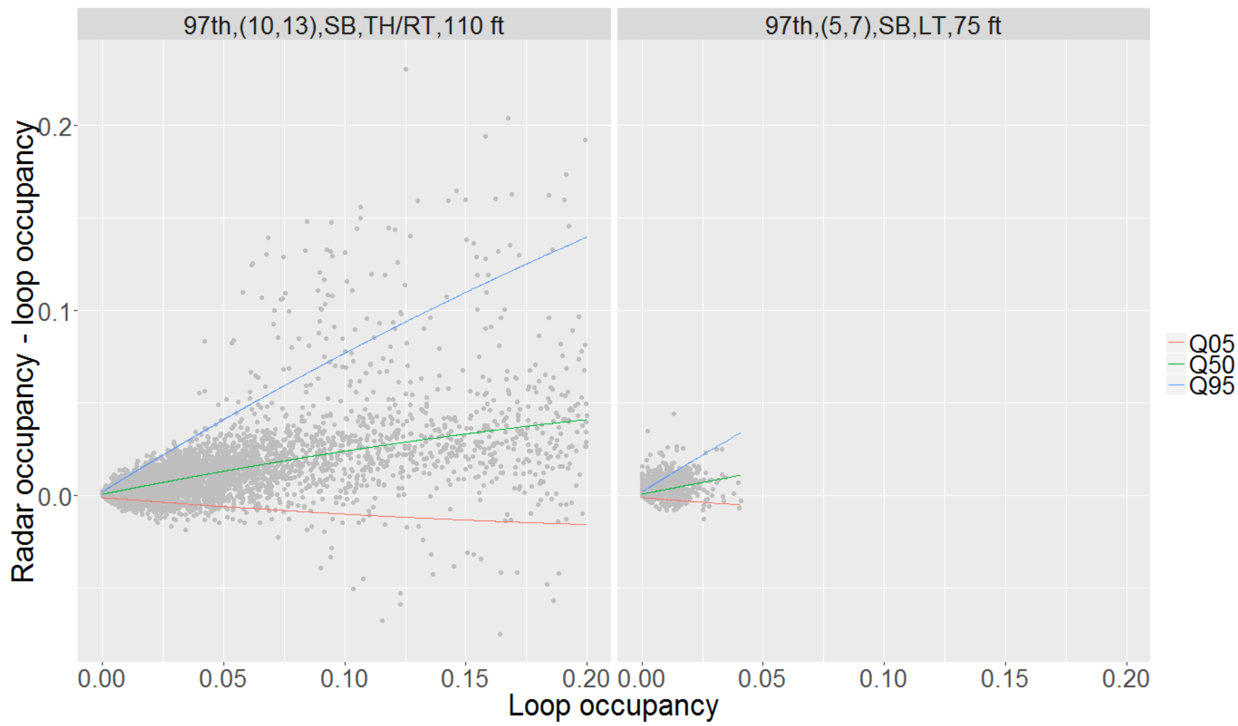


Figure 6.16: Fitted Occupancy Differences with the Quantile Regression Model of Advance Radar Sensors

6.5.3 Time to Gap Out (TTG)

Only one pair of loop and radar sensors, (10,13), at the southbound through lane of the 97th Avenue & SE Lawnfield Road, is available for TTG analysis. The radar TTGs versus loop TTGs along with video vs loop TTG for the same site are shown in Figure 6.17 and Figure 6.18, respectively. For the radar sensor, 91.1% of the gap out falls under normal regime as defined previously. For the same location, video has 91.2% of gap-out that fall under normal regime. Thus for this site the TTG performance between video and radar is comparable. A model was not constructed because there was only one zone for analysis. Further study is needed to assess transferability of these results.

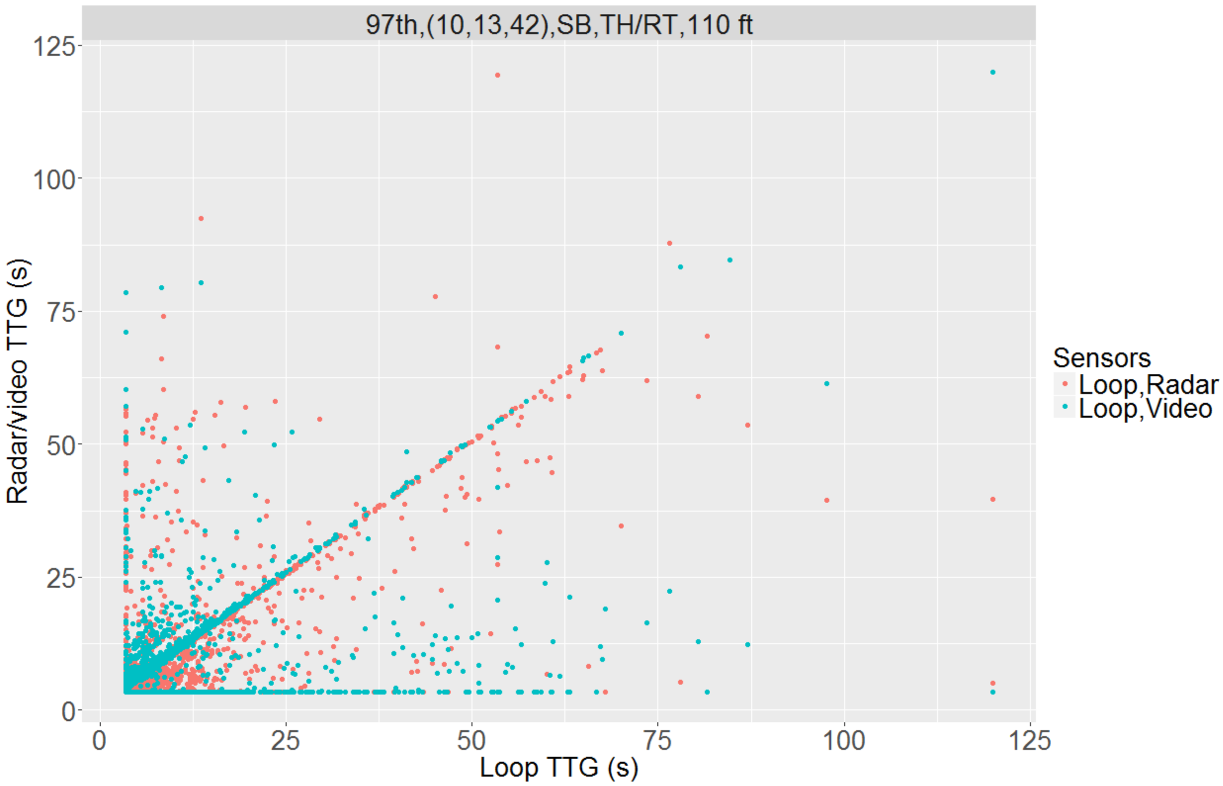


Figure 6.17 Histogram of the Ratio of Radar TTGs to Loop TTGs

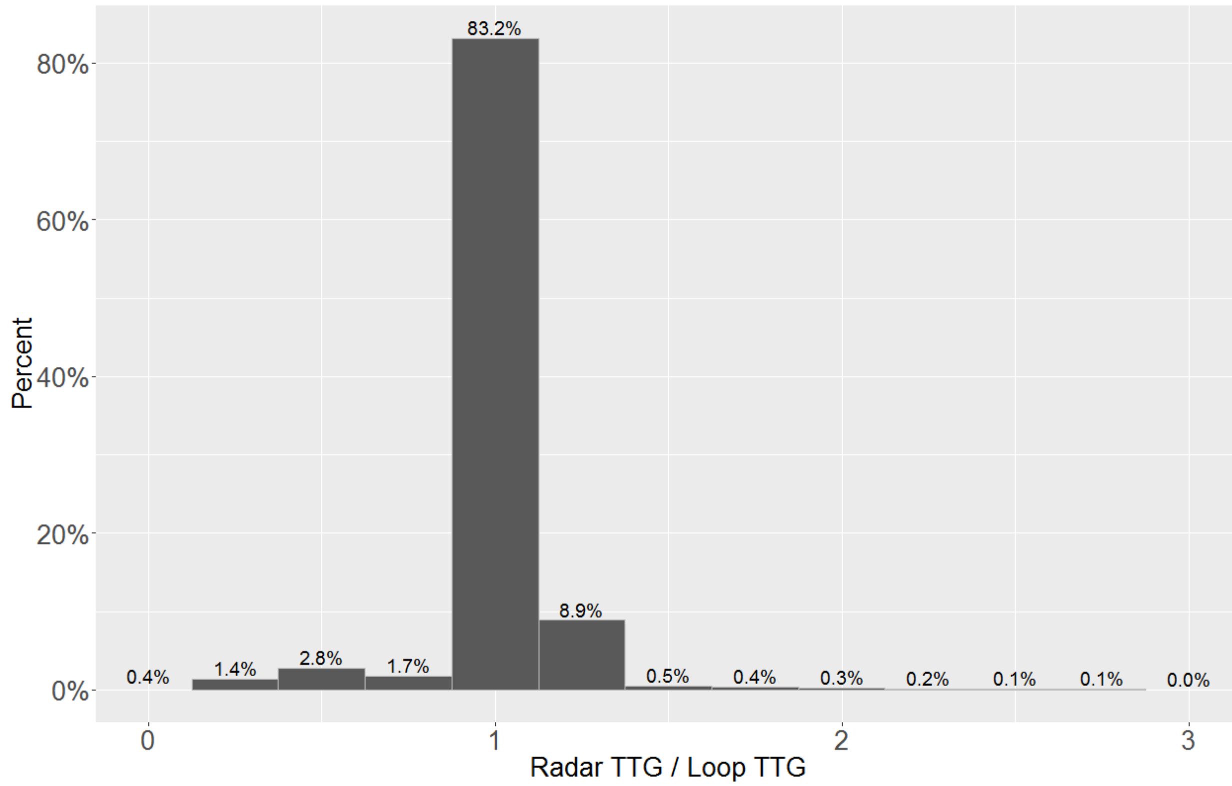


Figure 6.18: TTGs of Sensors (10, 13, 42) (Loop, Radar, Video)

6.6 SUMMARY

In this chapter the impacts of using non-invasive technology for advance detection were analyzed. This study focused on the scenario when the non-invasive detector was mounted on the mast arm / luminaire on the far side of the intersection (with the exception of the radar at 97th) and an attempt was made to simulate a loop detector anywhere between 75 ft – 200 ft in advance of the stop bar. Figure 6.19 shows the range of activation differences between video and loop activations. It can be seen that activation differences under the observed conditions had an error range of (-10 to 2) activations per 5-minute period. Most of the video activations are lower than those observed by loop detectors. It should be noted that maximum activations observed at the studied sensors ranged from 20 to 60 activations for each 5-minute interval. So, if the stop-bar mounted video sensor were to be used for an advance sensor the change threshold should account for errors that can be as high as 50% in some cases, causing serious operational issues. Site specific conditions tend to impact the difference range significantly with the 97th intersection experiencing a lower difference range as compared to Wilsonville and the 122nd intersections. These differences can be attributed to any of the various differences that occur between the sites, such as mounting height (the 97th intersection has video detector located at higher vantage point), traffic volume, and video sensing technology. Further research is needed to investigate the differences in the video sensor performance. Based upon this work, it is not recommended to gather advance vehicle counts / activations with a stop bar mounted video sensor at this time. While radar sensors were available at two locations, their performance was a mixed bag. At one location, radar performance was more consistent with loop as compared to the video whereas at the other location this trend was reversed. More work is need to further investigate the radar sensors prior to making a recommendation.

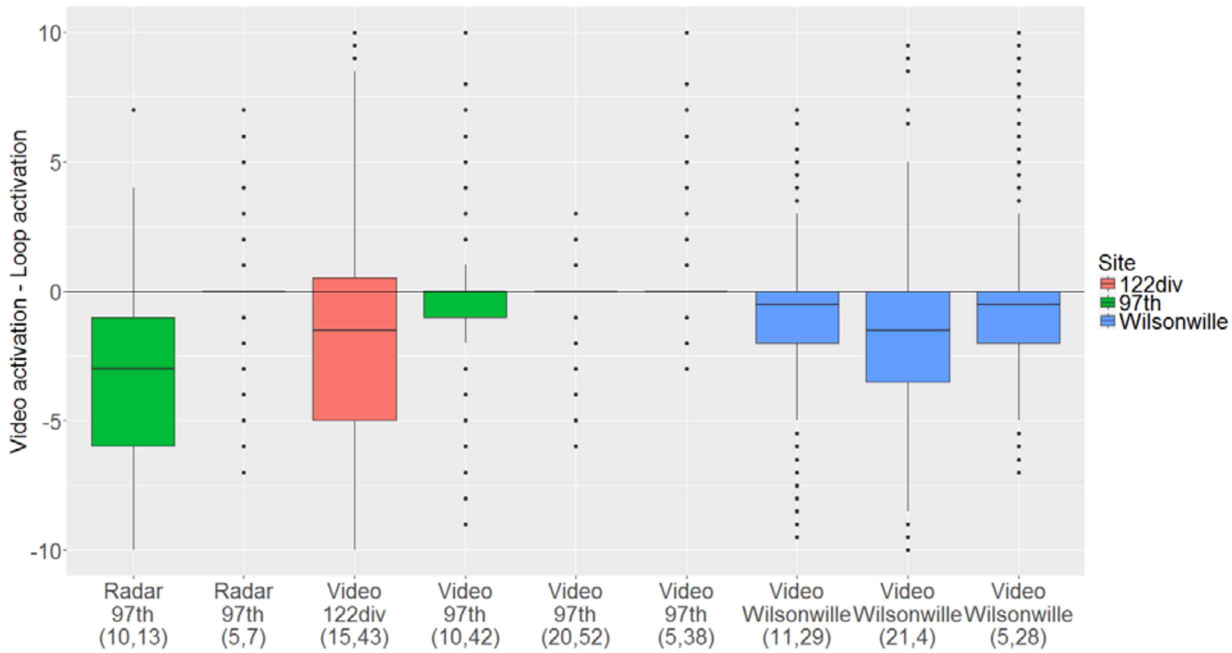


Figure 6.19: Activation Differences of Advance Sensors

The video occupancy differences result are shown in Figure 6.20. The discrepancy between loop and video is very stark especially for the 122nd site with discrepancies being as high as 0.5 for some instances while performance at the 97th site was reasonable. Again further studies need to be conducted to differentiate the cause of discrepancy in terms of height of sensor, traffic volumes (queue backup over the sensor), and sensor technology. Based on quantile regression modeling, it was found that the relationship of both video occupancy and activation with loop occupancy and activation is non-linear with better performance during low and oversaturated traffic conditions and more discrepancies during medium to heavy traffic conditions. Finally, daytime and left turn lane were not found to have a major impact on activation or occupancy discrepancy. As such, at this point it is not recommended to generate occupancy in an advances detection zone with a stop bar mounted video sensor. Radar overall performance at 97th intersection seems reasonable but at this site video also seems to function within reason, indicating that site conditions may play as important a factor as choice of non-invasive technology in performance at this metric. Based upon this work, radar looks promising for gathering occupancy at an advanced zone, but corroboration of these results at additional sites would be necessary prior to recommending this technology.

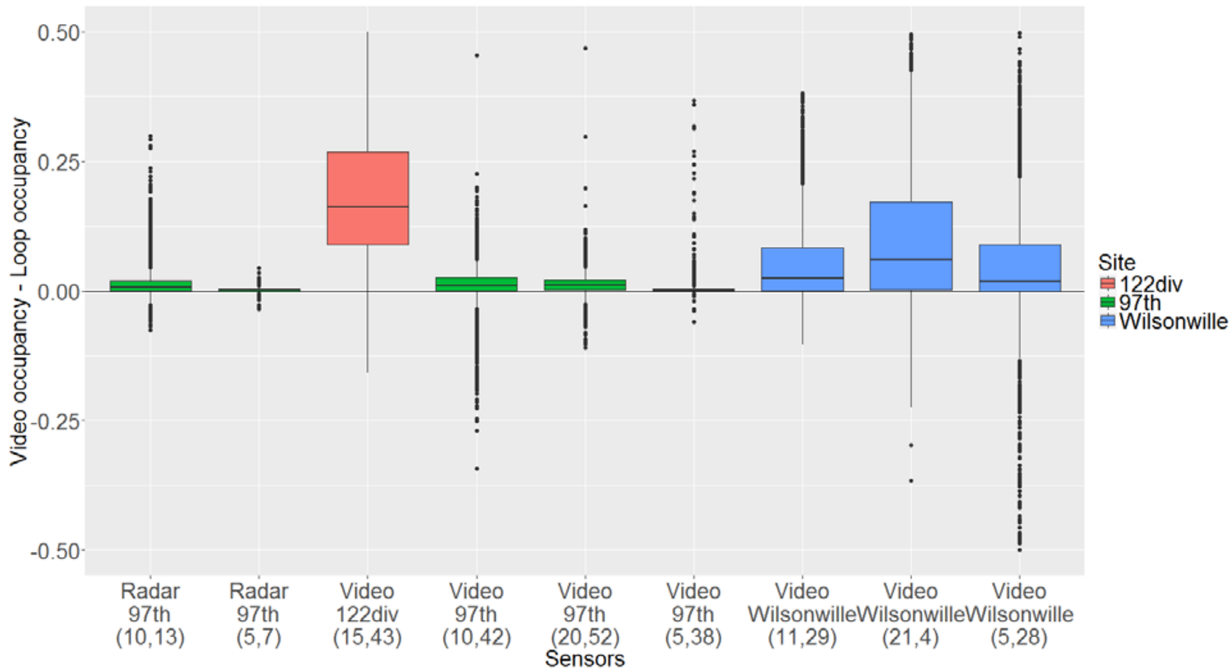


Figure 6.20: Occupancy Differences of Advance Sensors

With respect to TTG performance shown in Figure 6.21, it was found that on average ideal behavior, when the loop and video gap out relatively close to each other temporally (normal data), is only observed in approximately 68% of the cases. Additionally, early gap out was observed for 9% of the cases and late gap out in 20% of the cases as compared to the loop sensor. However, this also varied significantly between intersections. For the non-invasive sensors at the 97th intersection, regardless of non-invasive technology (video or radar), most of the data belongs to the normal regime. The video sensors at the 122nd intersection have the least normal data. Again, additional work is need to understand the impact of other factors (mounting height, traffic volumes, and sensor technology), but based upon this work, radar looks promising for determining gaps in an advanced detection zone but stop bar mounted video would not.

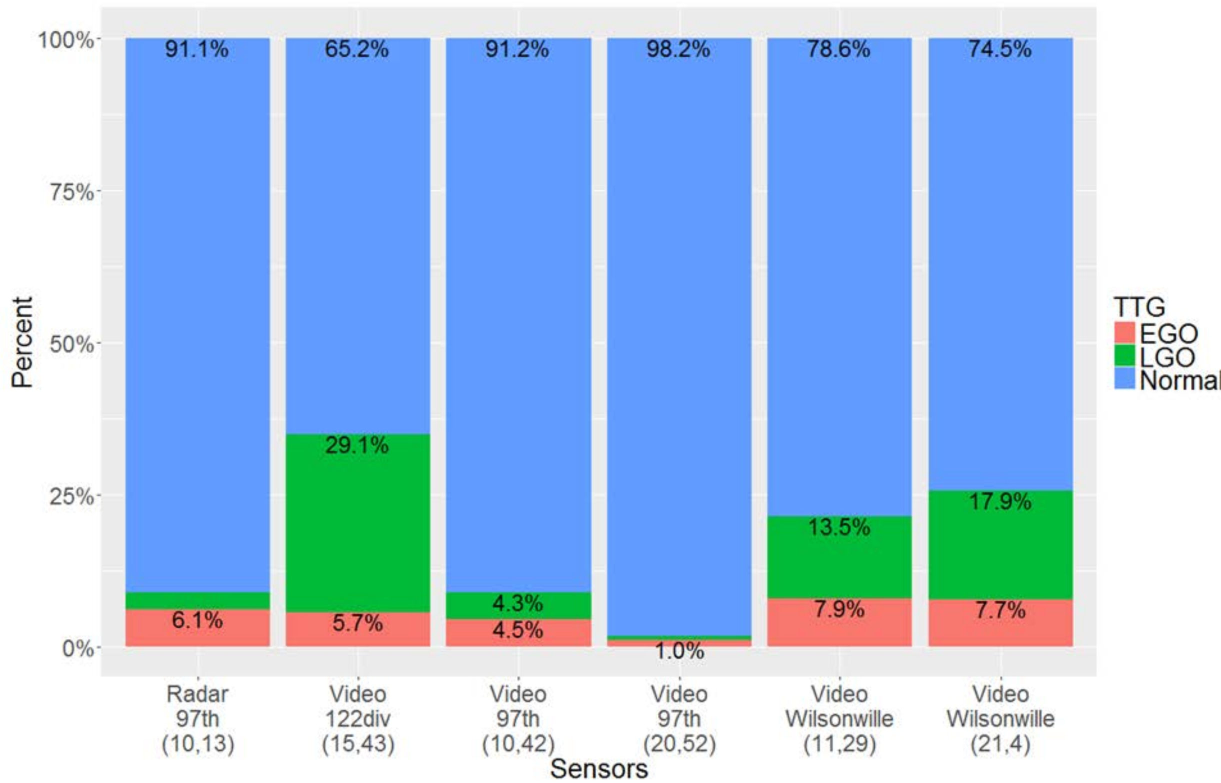


Figure 6.21: TTG Compositions of Advance Sensors

7.0 STOP BAR SENSOR ANALYSIS

Stop bar sensors are commonly used for end of queue detection using gap out logic, placing a call for service for a given phase, and calculating performance measures such as split failures, delay and others. Table 7.1 lists the performance measures used in this study to investigate discrepancies that might impact traffic signal operations when using a non-invasive detection device in place of an inductive loop detector. Time to gap out and time to first sustained call directly impact the ability for terminating green phase after an observed gap and for placing a call during red at the proper time. Also, a combination of green occupancy ratio (GOR) and Red Occupancy Ratio for the first 5 sec of red (ROR5) have been used to asses if there is a probability of split failure *(Day et al. 2014)*. High GOR accompanied by a high ROR5 value implies that the queue was not cleared at the end of green resulting in a split failure.

Following the logic used for advance sensor evaluation, only the loop sensors passing the reliability verification in Chapter 5.0 are used in the detailed analysis. Table 7.2 lists the sensors used for stop bar sensor evaluation. It should be noted that a total of 5 pairs were left after the filtering process, with the non-invasive sensors being video sensors. These pairs are located at Wilsonville Rd & Town Center, US 20 & Robal Road, and SE 122nd Avenue & Division Street. Four pairs of sensors are located in left-turn lanes, with one pair of sensors in a through lane.

Subsequent section discuss the performance of these sensors on the performance measures described in Table 7.1.

Table 7.1: Performance Measures Used to Assess the Non-Invasive Sensors

	Stop bar Sensor			
Performance Measure	*Time to gap out (Gap >2.0 s)*	*Green Occupancy Ratio*	*Red Occupancy Ratio (first 5 sec)*	*Time to First Sustained Call during Red Time*
Definition	Time to find first gap greater than 2 second during a green interval	Percentage of green time for which detector was turned on	Percentage of first 5 seconds of red time for which the detector was occupied	Time from the start of red interval when a call was placed which lasted for the remaining red duration
Use in Traffic Control	Used for implementing a gap out logic to terminate the active green phase	GOR + ROR5 are together used to detect split failure		Used for placing a call for service by a given phase. It is also used to calculate delay by some algorithms

Table 7.2: Stop Bar Sensors Passing the Ground Truth Verification

No	Intersection	Signal phase	Sensors	Direction	Location
1	SW Wilsonville Rd & Town Center Loop West	7	(17,22)	SB	LT
2		7	(18,7)	SB	TH
3		5	(6,8)	EB	LT
4	US 20 & Robal Road	5	(6,26)	SB	LT
5	SE 122nd Avenue & Division Street	5	(5,38)	EB	LT

7.1 TTG COMPOSITIONS

A major function of stop bar sensors is to detect the end of queue by observing the gaps between vehicles. This study uses a gap out threshold value of 2 seconds to identify this gap for both video and loop sensors for every green duration observed in the field (it is noted that in practice this value is site, traffic, and speed dependent). All the data are divided into four types depending on whether sensors identify eligible gaps in green time:

- "L_g1V_g0": The loop sensor finds the eligible gaps, but not the video sensor. In this case, operation with the video sensors may excessively extend the active phase.
- "L_g1V_g1": Both of the sensors find a gap greater than 2 sec. This implies that video and loop are functioning in a similar manner.
- "L_g0V_g1": The video sensor gaps out but the loop sensor doesn't. Presuming that the loop is functioning correctly, this implies that video will gap out when the queue is still being served.
- "L_g0V_g0": Both of the two sensors do not find the eligible gaps. This implies that video and loop are functioning in a similar manner.

The statistics of TTGs for each pair of stop bar sensors are summarized in Table 7.3 and Table 7.4. The main points to be noted are that the desired condition with either both loop and video finding a gap or both not finding a gap happen during 81% of green indications across all the intersections. There is a significant site by site difference with the best site (SE 122nd Avenue & Division Street) producing consistent results for 97% of time whereas worst site (US 20 & Robal Road) only produced consistent results 67% of the time. For the other cases, L_g1V_g0 is the more common of the two, happening 18% of time compared to L_g0V_g1 occurring in only 1% of the cycles. It should be noted that L_g1V_g0 error is more prominent during night time as compared to the day time. A possible explanation is that the head light from the vehicles might place the call earlier than placed by loop thus increasing the sensor occupancy durations.

Table 7.3: TTG Compositions of Each Pair of Stop Bar Sensors

No	Intersection	Sensors	Count	L_g1V_g1	L_g1V_g0	L_g0V_g1	L_g0V_g0
1	SW Wilsonville Rd & Town Center Loop West	(17,22)	14249	88.4%	8.8%	0.1%	2.6%
2		(18,7)	14249	31.0%	18.7%	2.7%	47.5%
3		(6,8)	18254	14.8%	31.1%	0.7%	53.4%
4	US 20 & Robal Road	(6,26)	5291	94.1%	1.2%	1.4%	3.3%
5	SE 122nd Avenue & Division Street	(5,38)	14479	0.7%	15.2%	1.2%	82.8%
	Total		66522	37.2%	17.8%	1.2%	43.7%

Table 7.4: Distributions of L_g1V_g0 Data in Daytime and Night

No	Intersection	Sensors	Lg1Vg0 proportion in daytime	Lg1Vg0 proportion at night
1	SW Wilsonville Rd & Town Center Loop West	(17,22)	5.2%	13.1%
2		(18,7)	11.6%	27.3%
3		(6,8)	12.2%	54.8%
4	US 20 & Robal Road	(6,26)	1.5%	0.4%
5	SE 122nd Avenue & Division Street	(5,38)	8.6%	25.2%

7.1.1 L_g1V_g1 TTG Data Analysis

The L_g1V_g1 condition was further investigated to understand whether or not the gap-out happens in a consistent manner. A scatter plot with video TTG vs. loop TTG for L_g1V_g1 data is shown in Figure 7.1. Figure 7.2 shows the histogram of the ratio of video TTGs to loop TTGs. The scatter plots of video TTG vs loop TTG for each pair of sensors can be seen in Figure 7.3.

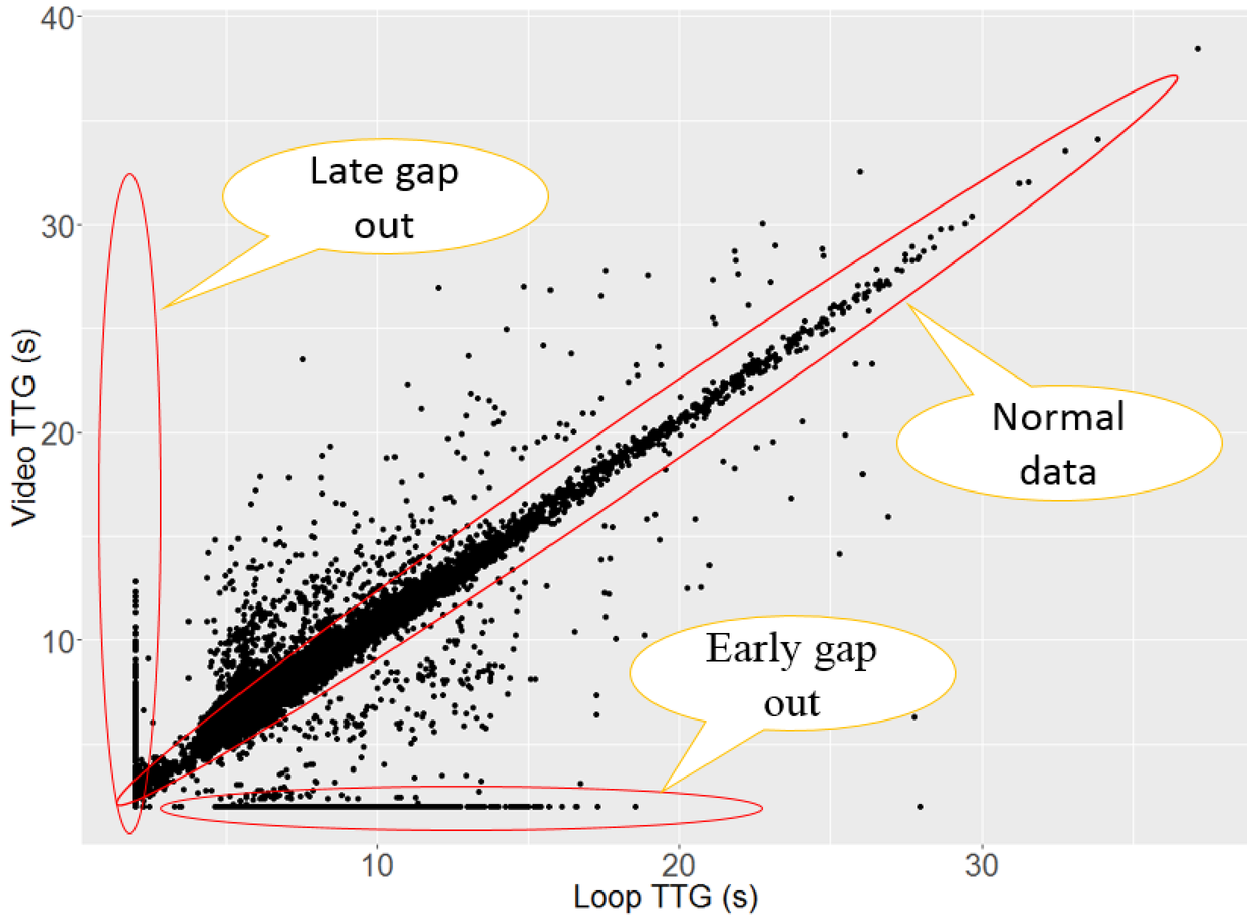


Figure 7.1: Lg1Vg1 TTG Data of Coupled Stop bar Sensors

Similar to the advance sensors, the TTGs of stop bar sensors also can be divided into three types (Figure 7.1): normal data, where loop TTG and video TTG are consistent; EGO data, where loop TTGs are low, but the video TTGs are high; and LGO data, where loop TTGs are high, but video TTGs are low. As can be seen in the histogram (Figure 7.2), 84% of the data belong to the normal regime (sum of the two bars surrounding the 1.0 tick on the x-axis).

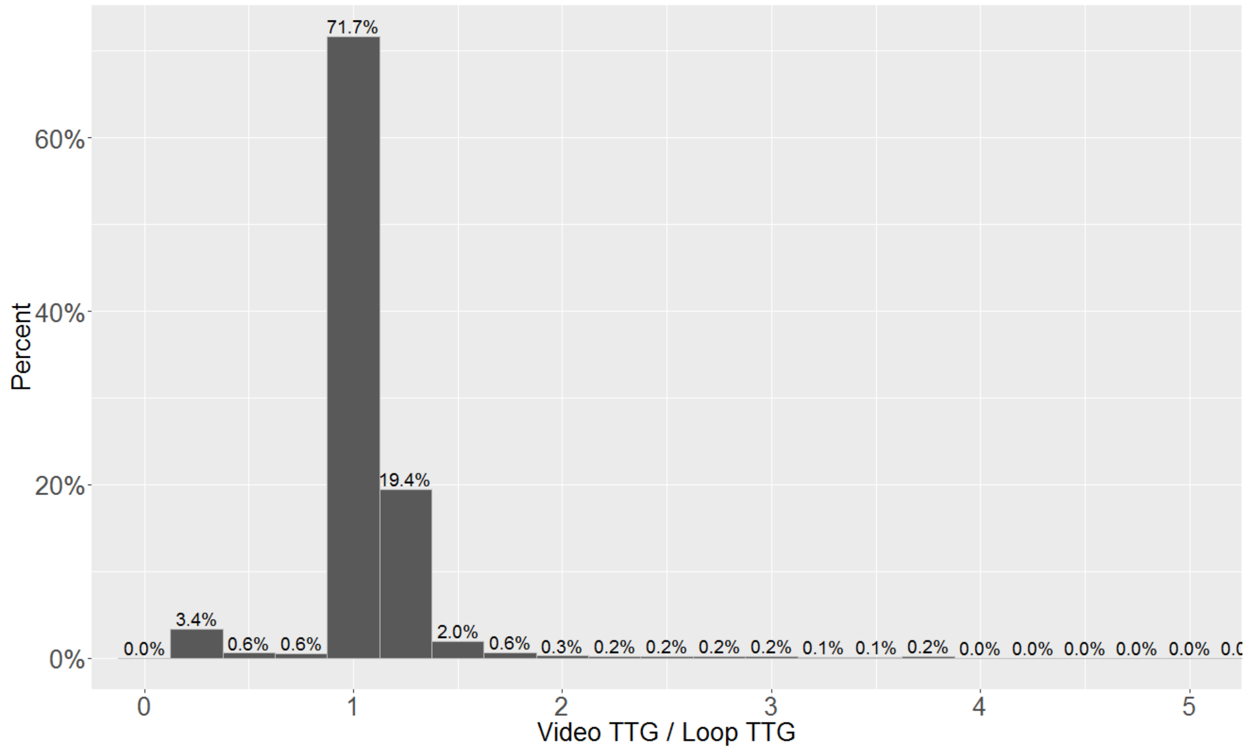


Figure 7.2: Histogram of the Ratio of Video TTGs to Loop TTGs

Looking at the scatter plots (Figure 7.3), the sensors (6,26) have several data points with either the loop TTGs or the video TTGs being larger. For the sensors (17,22), the video TTGs seem generally larger than the loop TTGs. The sensors (18,7) perform well. For the sensors (6,8), although most video TTGs and loop TTGs are consistent, some video TTGs are obviously larger than loop TTGs.

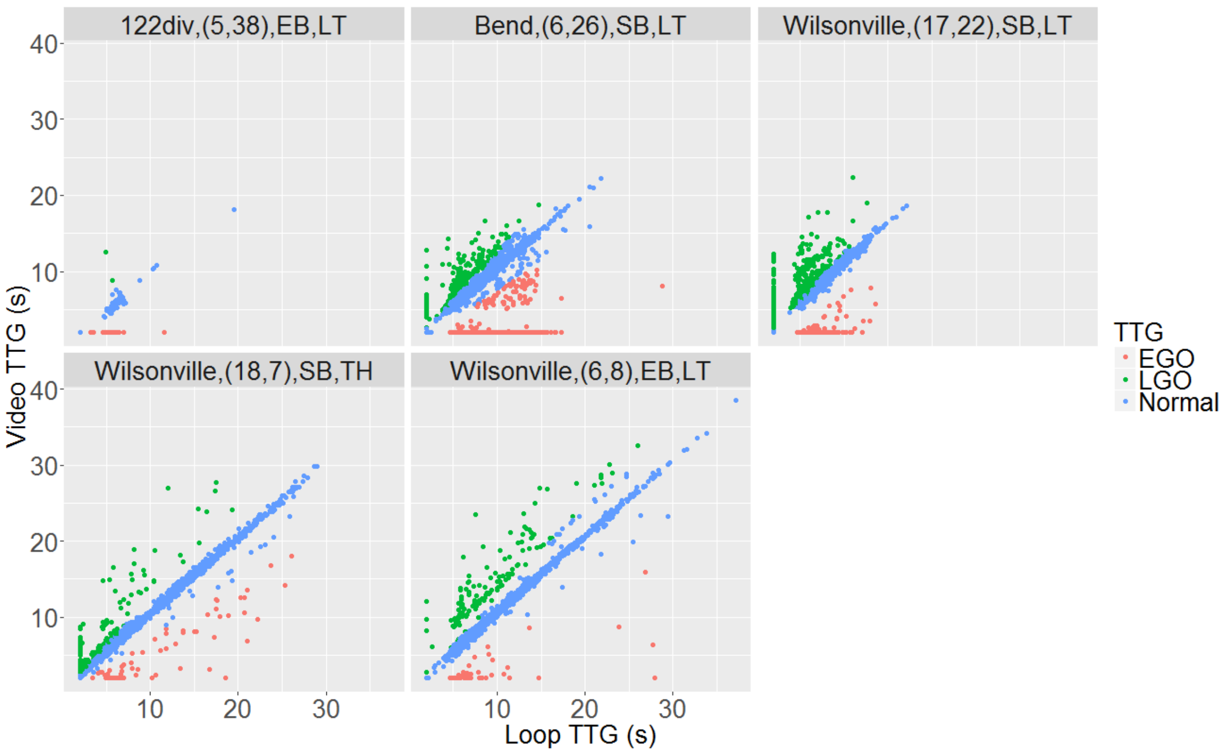


Figure 7.3: Lg1Vg1 TTG Data of Each Pair of Stop bar Sensors

Mathematical models were developed to find the statistically significant variables that impact the proportion of EGO and LGO present for a specific detector pair. Similar to the advance sensors, the MNL model is used and the final results are shown in Table 7.5.

Table 7.5: The Result of MNL Model of TTGs in Green Time

	EGO				LGO			
Variable	**Estimate**	**Std. Errors**	**P-value**	**Relative risk ratio**	**Estimate**	**Std. Errors**	**P-value**	**Relative risk ratio**
(Intercept)	-5.004	0.219	0.000*	0.007	-2.302	0.063	0.0008	0.100
Loop TTG	0.532	0.059	0.000*	1.703	0.215	0.047	0.000*	1.240
Loop TTG^2	-0.020	0.003	0.000*	0.980	-0.031	0.006	0.000*	0.970
Sensors (17,22)	-2.967	0.333	0.000*	0.051	0.468	0.187	0.012*	1.596
Sensors (5,38)	2.951	0.667	0.000*	19.117	-3.723	0.651	0.000*	0.024
Sensors (6,26)	0.722	0.244	0.003*	2.059	0.871	0.232	0.000*	2.388
Sensors (6,8)	0.463	0.352	0.188	1.588	0.709	0.273	0.009*	2.033
Loop TTG: (17,22)	1.284	0.155	0.000*	3.610	2.338	0.071	0.000*	10.362
Loop TTG: (5,38)	-0.552	0.318	0.083	0.576	3.963	0.989	0.000*	52.630
Loop TTG: (6,26)	-0.030	0.080	0.709	0.971	-0.056	0.095	0.557	0.946
Loop TTG: (6,8)	-0.622	0.099	0.000*	0.537	-0.192	0.077	0.013*	0.826
Loop TTG^2: (17,22)	-0.134	0.016	0.000*	0.875	-0.378	0.013	0.000*	0.685
Loop TTG^2: (5,38)	0.013	0.031	0.670	1.013	-0.794	0.342	0.020*	0.452
Loop TTG^2: (6,26)	-0.003	0.005	0.519	0.997	-0.002	0.010	0.821	0.998
Loop TTG^2: (6,8)	0.025	0.004	0.000*	1.025	0.028	0.006	0.000*	1.029
Daytime	-0.647	0.086	0.000*	0.523	0.536	0.057	0.000*	1.708
Lane type - LT	1.169	0.263	0.000*	3.218	-1.675	0.187	0.000*	0.187
Residual Deviance: 18572.55. AIC: 18636.55								

Note: * significant at 0.05 level.

Since normal data is taken as the base case in the MNL model, the relative risk ratio means the relative probability of data being EGO/LGO compared to the normal data. It was found that the TTG variable shows significantly non-linear effects on both the EGO and LGO data and this effect varies by site. This can be seen in Figure 7.3 where the error rates are higher in the middle region and not linearly increasing and decreasing with TTG. This is in line with our observation (in Chapter 6.0) previously that performance during moderate volume is worse than completely saturated or very low volume conditions.

The salient insights as obtained from the MNL model are listed below:

- *Loop TTG*: The loop TTG shows significantly non-linear effects on both the EGO and LGO data. In addition, both the coefficients of the squared TTG for EGO and LGO data are negative. That is, with the increase of loop TTG, at first the data trends away from normal, but after loop TTG passes a point, it tends toward normal.

- *Sensors*: The location of video sensors also show significant influences. Compared with the sensors (18,7), the data of sensors (17,22) are more likely to be the LGO data. However, the data of sensors (5,38) are more likely to be EGO data. For the other two couples of sensors, the data are less likely to be the normal data.

- *Daytime*: The variable daytime shows significantly negative effects in EGO data model, but positive effects in LGO data model. That is, the data are less likely to be EGO data, and more likely to be LGO data in daytime. One possible reason can be higher chances of detection zone activation during daytime would decrease the early gap-out probability.

- *Lane type*: Lane type shows significantly positive effects on the early gap out, but negative effects on the late gap out. That is, the data pertaining to the left-turn lane are more likely to be classified as early gap out, but not late gap out. This might be due to vehicles on left turn lanes being missed due to occlusion from main line vehicles.

In summary, similar to that which was seen in the advanced sensor analysis, the video sensors perform reasonably consistent to the loops during very low volume as well as very high volume periods with decreased performance with moderate volumes. This suggests that video would perform well as a surrogate for loops in locations with these conditions. Deployments should expect to see modest variance in performance during moderate volume periods. Other variables explored appear to impact the performance of this metric, but further analysis would be needed to isolate the impact of those variables.

7.2 TIME TO FIRST SUSTAINED CALL (TFSC) IN RED TIME

Time to first sustained call (TFSC) is the time when the first call is placed that is sustained until the end of red. TFSC is the time when call will be placed in the control to request right of way for the phase. TFSC values were obtained for each red duration for both video and loops.

7.2.1 TFSC Compositions

Similar to the previous section, all the data can be divided into four types depending on the performance of the sensor. In this case, it is dependent upon whether or not the sensor finds the eligible TFSCs:

- "$L_{SC}1V_{SC}0$": The loop sensor finds the eligible TFSC, but not the video sensor. In this case, the video sensor may miss the call for service.

- "$L_{SC}1V_{SC}1$": Both sensors find the eligible TFSC.

- "$L_{SC}0V_{SC}1$": The video sensor finds an eligible TFSC but not the loop sensor. Presuming the loop is reliable, this suggests that the video sensor may be placing a false call, resulting in wasted green time.

- "$L_{SC}0V_{SC}0$", both of the sensors do not find the eligible TFSC.

Both $L_{SC}1V_{SC}1$ and $L_{SC}0V_{SC}0$ data are desired in field, whereas $L_{SC}1V_{SC}0$ and $L_{SC}0V_{SC}1$ are less desired. The TFSC distributions of each pair of stop bar sensors are summarized in Table 7.6.

Table 7.6: TFSC Compositions of Stop Bar Sensors

No	Intersection	Sensors	Count	$L_{SC}1V_{SC}1$	$L_{SC}1V_{SC}0$	$L_{SC}0V_{SC}1$	$L_{SC}0V_{SC}0$	$L_{SC}1V_{SC}1$+ $L_{SC}0V_{SC}0$
1	SW Wilsonville Rd & Town Center Loop West	(17,22)	14244	34.0%	1.6%	2.8%	61.6%	95.6%
2		(18,7)	14244	75.3%	1.9%	3.7%	19.0%	94.3%
3		(6,8)	18249	90.6%	8.8%	0.0%	0.6%	91.2%
4	SE 122nd Avenue & Division Street	(5,38)	14463	99.5%	0.4%	0.0%	0.0%	99.5%
5	US 20 & Robal Road	(6,26)	5293	73.7%	16.9%	0.6%	8.8%	82.5%
	Total		86513	81.0%	3.9%	1.1%	14.0%	95.0%

Overall, 95% of data belong to the desired states, $L_{SC}1V_{SC}1$ or $L_{SC}0V_{SC}0$. However, the sensors (6,8) at the Wilsonville intersection and (6,26) at the Bend intersection do have relatively large $L_{SC}1V_{SC}0$ data.

Further investigation is made into the $L_{SC}1V_{SC}1$ data to check for a numerical correlation between the TFSC values obtained for video and loop detectors.

7.2.2 $L_{SC}1V_{SC}1$ Data Analysis

For the $L_{SC}1V_{SC}1$ data, the loop TFSCs versus the video TFSCs of all the stop bar sensors are shown in Figure 7.4. The red line in Figure 7.4 is a straight line passing the origin point with the slope being 1. Figure 7.5 shows the histogram of the ratio of video TFSCs to the loop TFSCs. It can be seen that most video TFSCs are consistent with the loop TFSCs, i.e. belonging to the normal data. 88.4% of the total data has the ratio of the video TFSCs to the loop TFSCs between 0.75 and 1.25. In addition to normal data, early call data are also present, where the video TFSCs are larger than the loop TFSCs, and late call data, where the video TFSCs are smaller than the loop TFSCs. The TFSCs of each pair of stop bar sensors are shown in Figure 7.6.

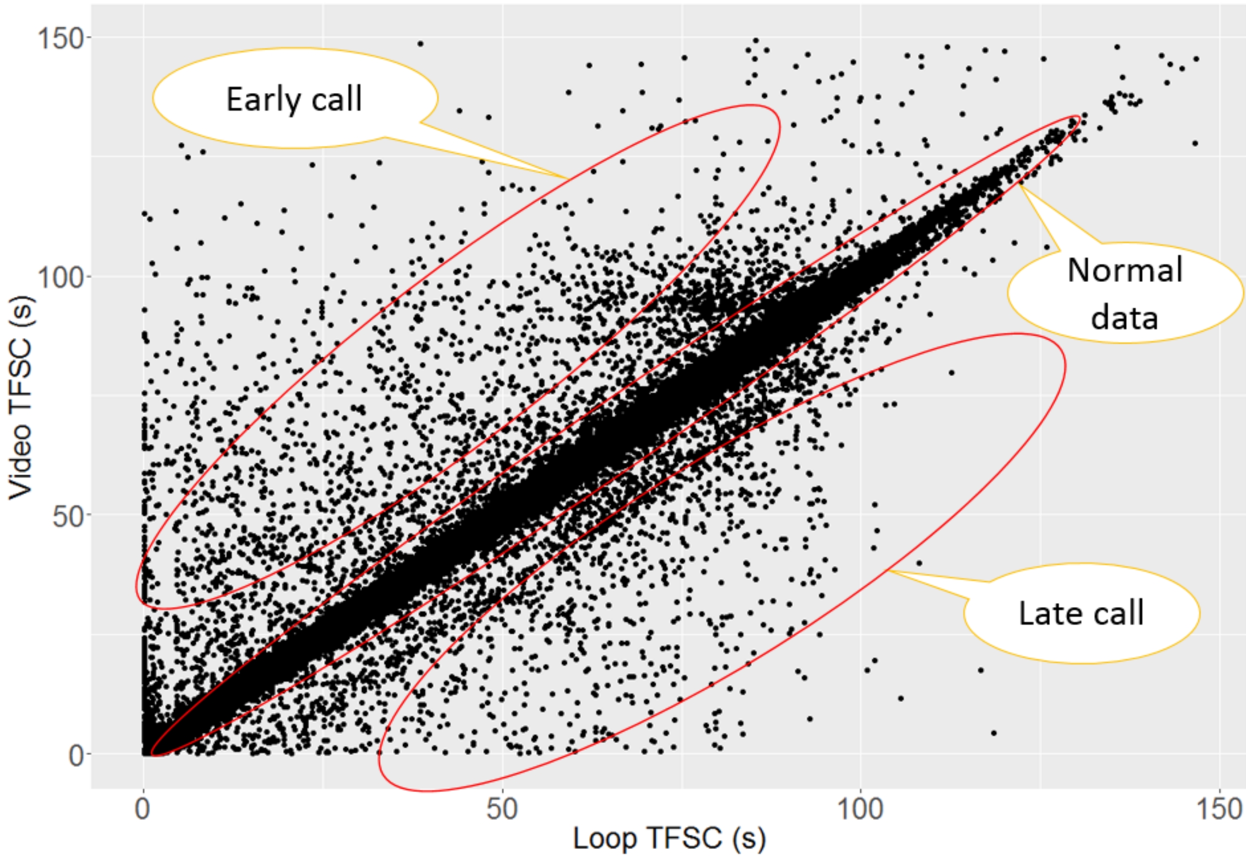


Figure 7.4: Loop TFSC vs Video TFSC of Stop bar Sensors

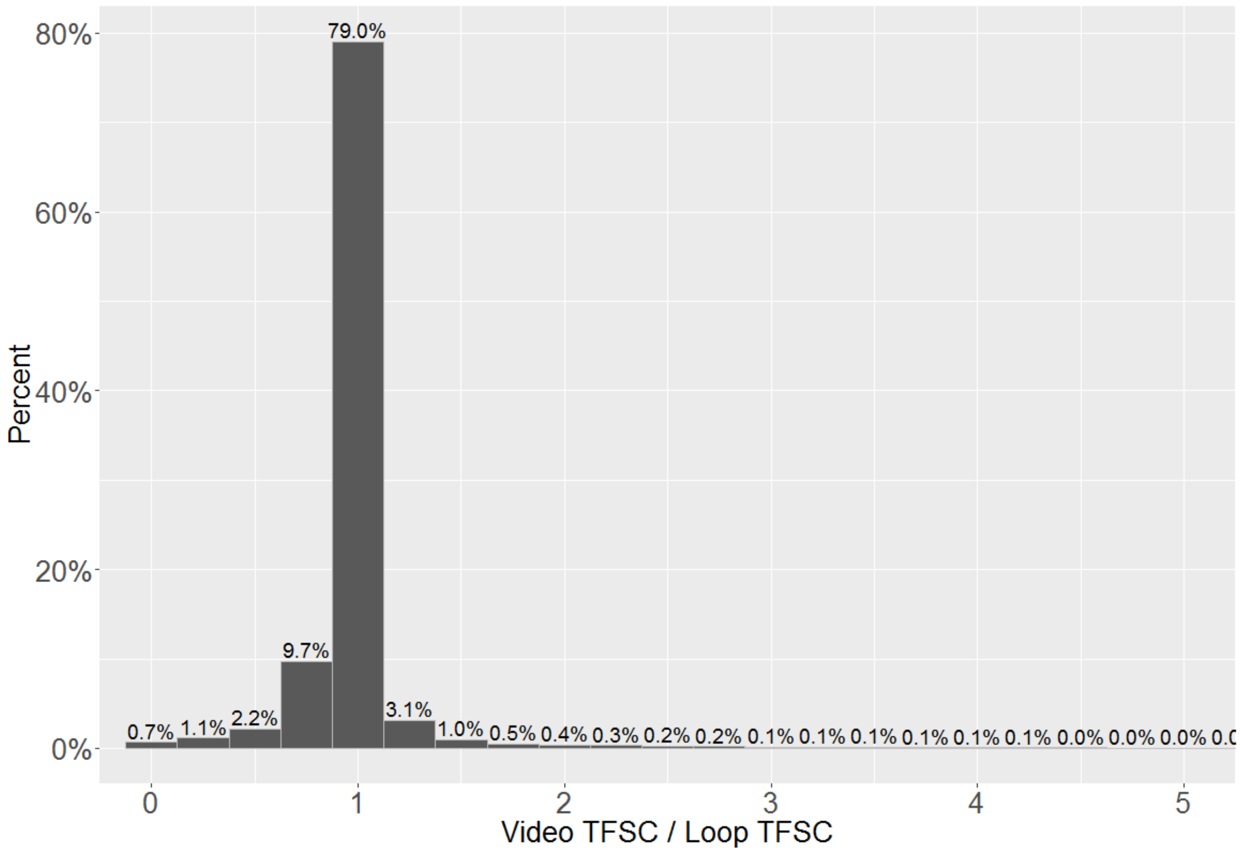


Figure 7.5: Histogram of the Ratio of Video TFSC to Loop TFSC

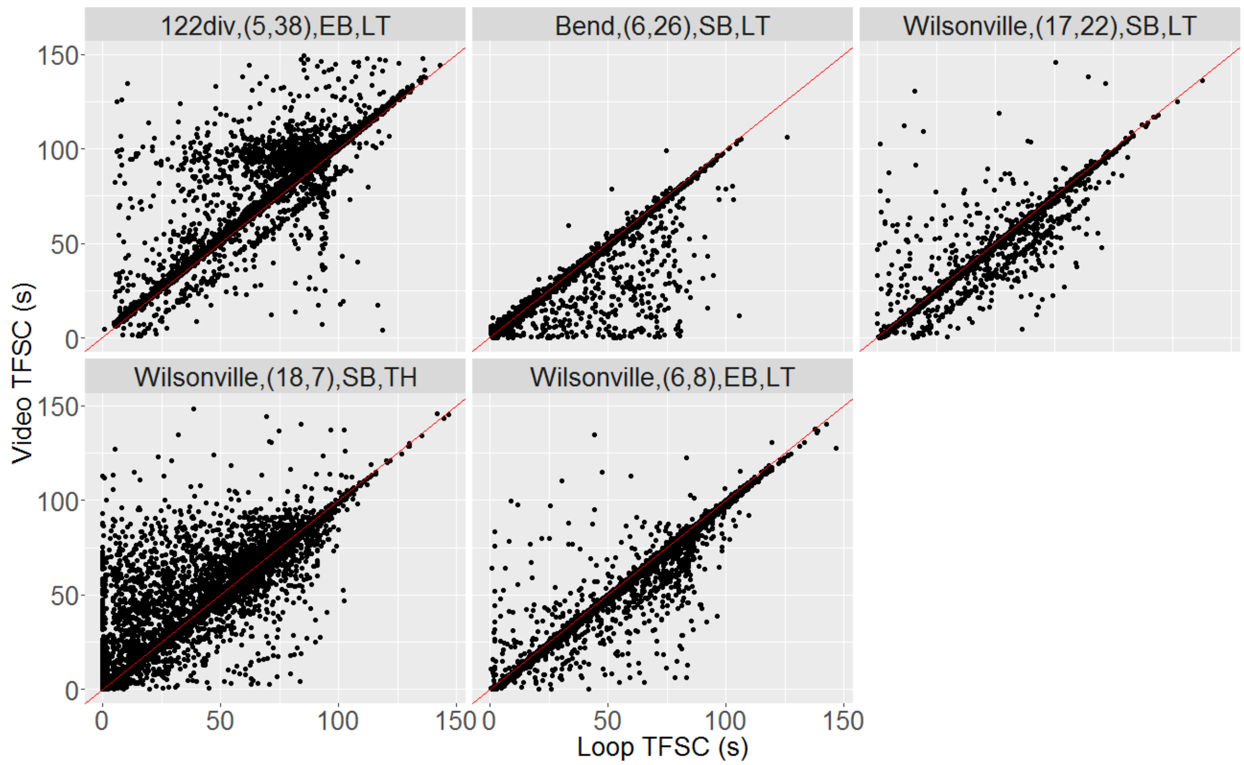


Figure 7.6: Loop TFSCs vs Video TFSCs of Each Pair of Stop bar Sensors

Overall, there is a prominent linear trend between video TFSC and loop TFSC with the unit slope shown in both Figure 7.4 and Figure 7.6. This implies that in most cases the video is able to place a call around the same time as loop, however there are certain anomalies that are observed at the different sites. At the SE 122nd Avenue & Division Street, there are many data points with the video TFSCs being around 100s while the loop TFSCs are scattered. Based on video exploration it was found that at times video sensor 38 was often stuck in the "ON" status even when no vehicles exist (Figure 7.7). It is hypothesized that video sensors may be activated by the vehicles in adjacent lanes.

At the US 20 & Robal Road, the loop TFSCs generally show a linear relationship with the video TFSCs. It also needs to be noted that there are certain cases when the video TFSCs tend to be smaller than loop TFSC. This implies that the loop tended to activate earlier than the video sensor.

At the SW Wilsonville Rd & Town Center Loop West, the video TFSCs show clear linear trends with the loop TFSCs. Compared with the sensors (6,8) and (17,22), the data of the sensors (18,7) is more dispersed. Since this pair of sensors is located at the through lane, higher traffic volumes are expected. It is believed that high volume may contribute to this problem, since it may be more difficult for video sensors to distinguish the consecutive vehicles. Data from additional stop bar sensors located in through lanes would be needed to produce generalizable results.

In addition, some data of the sensors (5,38) and (17,22) show another linear trend under the main linear trend line implying that the video sensors may systematically underestimate the TFSCs for these data, however the exact cause was not identified.

Figure 7.7: Video Sensor 38 Was Stuck in “ON” Status When No Vehicles Existed

Statistical models were developed to find the statistically significant variables that impact the proportion of early call and late call present for a specific detector pair. The MNL model is used again here with the results shown in Table 7.7. Since the normal data is taken as the base case in the MNL model, the relative risk ratio refers to the relative probability of data being early call/late call data compared to the normal data.

Table 7.7: The Result of the MNL Model of TFSC

	Early call				Late call			
Variable	**Estimate**	**Std. Errors**	**P-value**	**Relative risk ratio**	**Estimate**	**Std. Errors**	**P-value**	**Relative risk ratio**
(Intercept)	-0.273	0.015	0.000*	0.761	4.186	0.027	0.000*	65.786
Loop TFSC	-0.105	0.004	0.000*	0.900	-0.261	0.014	0.000*	0.770
Loop TFSC^2	0.001	0.000	0.000*	1.001	0.002	0.000	0.000*	1.002
Daytime	-0.829	0.027	0.000*	0.436	-2.526	0.032	0.000*	0.080
Intersection-122div	-3.064	0.000	0.000*	0.047	-2.505	0.003	0.000*	0.082
Intersection-Wilsonville	-0.120	0.013	0.000*	0.887	-4.374	0.023	0.000*	0.013
Lane type - LT	0.953	0.016	0.000*	2.593	-2.512	0.012	0.000*	0.081
Loop TFSC: 122div	0.060	0.007	0.000*	1.061	0.227	0.014	0.000*	1.255
Loop TFSC : Wilsonville	-0.063	0.004	0.000*	0.939	0.178	0.014	0.000*	1.195
Loop TFSC^2: 122div	-0.001	0.000	0.000*	0.999	-0.002	0.000	0.000*	0.998
Loop TFSC^2: Wilsonville	0.000	0.000	0.000*	1.000	-0.002	0.000	0.000*	0.998
Daytime: 122div	0.157	0.001	0.000*	1.171	2.523	0.010	0.000*	12.469
Daytime: Wilsonville	1.342	0.023	0.000*	3.826	3.286	0.022	0.000*	26.728
Residual Deviance: 31676.77. AIC: 31728.77.								

Note: * significant at 0.05 level.

The salient insights as obtained from the MNL model are listed below:

- *Loop TFSC*: The loop TFSC shows significant non-linear effects on both the early call and late call data. The combined effects of the squared loop TFSC and loop TFSC are, with the increase of the real TFSC, the data are less likely to be either the early call or late call data. That is, the data tend to be normal under the high TFSC, which implies higher vehicular demand. This is also consistent with the previous finding that during higher demands, differences are lower.

- *Daytime*: Daytime shows significantly negative effects in both models. That is, the data are more likely to be the normal data in daytime than at night. It implies that the video sensor performance may have more problems at night.

- *Intersection*: The location of video sensors also shows significant influences. Compared with the Bend intersection, the data at the 122nd Avenue & Division Street are less likely to be the normal data, which can be seen from Figure 7.6. Compared with the Bend intersection, the data at the Wilsonville Rd & Town

Center West are more likely to be late call data, but less likely to be early call data.

- *Lane type*: The left turn lane shows significantly positive effects on TFSC. This might be due to vehicles on adjacent lanes placing a false call.

In summary, as was seen before, the video sensor is more consistent with the loop output when traffic volumes are higher. When placing a call at night, the temporal placement of the video call tends to differ much more than in the daytime. Lastly, as was seen in almost all previous models, the location of the sensors has an impact on the comparison; however additional data would be necessary to develop generalizable results for these differences.

7.3 GREEN OCCUPANCY RATIO AND RED OCCUPANCY RATIO

As part of a suite of real time performance metrics based upon event data developed by researchers at Purdue University, stop bar occupancy can be used to evaluate phase utilization. The green occupancy ratio (GOR) is defined as the amount of stop bar detector occupancy taking place during green *(Day et al. 2014)*, shown in Equation 7.1.

Equation 7.1: Green Occupancy Ratio

$$\boldsymbol{GOR = \frac{T_{ON}}{T_{ON} + T_{OFF}}}$$

where T_{ON} and T_{OFF} are the total durations of detector on and off times during the green interval.

The red occupancy ratio during the first 5 seconds of red (ROR_5) can be used to measure whether there is left demand at the end of a cycle *(Day et al. 2014)*. The ROR during the 1st five seconds of red is shown in Equation 7.2.

Equation 7.2: Red Occupancy Ratio

$$\boldsymbol{ROR_5 = \frac{T_{ON}}{5}}$$

where T_{ON} is the detector occupancy during the 1st five seconds of red.

The combination of GOR and ROR_5 are used to evaluate of the split performance *(Day et al. 2014)*. When both GOR and ROR_5 are high, it indicates that the utilization is high, and the there is still leftover demand after the end of green interval. An example is shown in Figure 7.8.

- The points in the upper right quadrant indicate the likely split failures, especially the force-offs symbolized by the cycles, where $ROR_5 \geq 0.8$ and $GOR \geq 0.8$.

- The points in the lower right quadrant indicates the conditions near saturation. The high GOR and zero ROR_5 suggest the efficient phase operation rather than a split failure.

- The upper and lower left quadrants indicate the under-saturated conditions, since the GOR values are low.

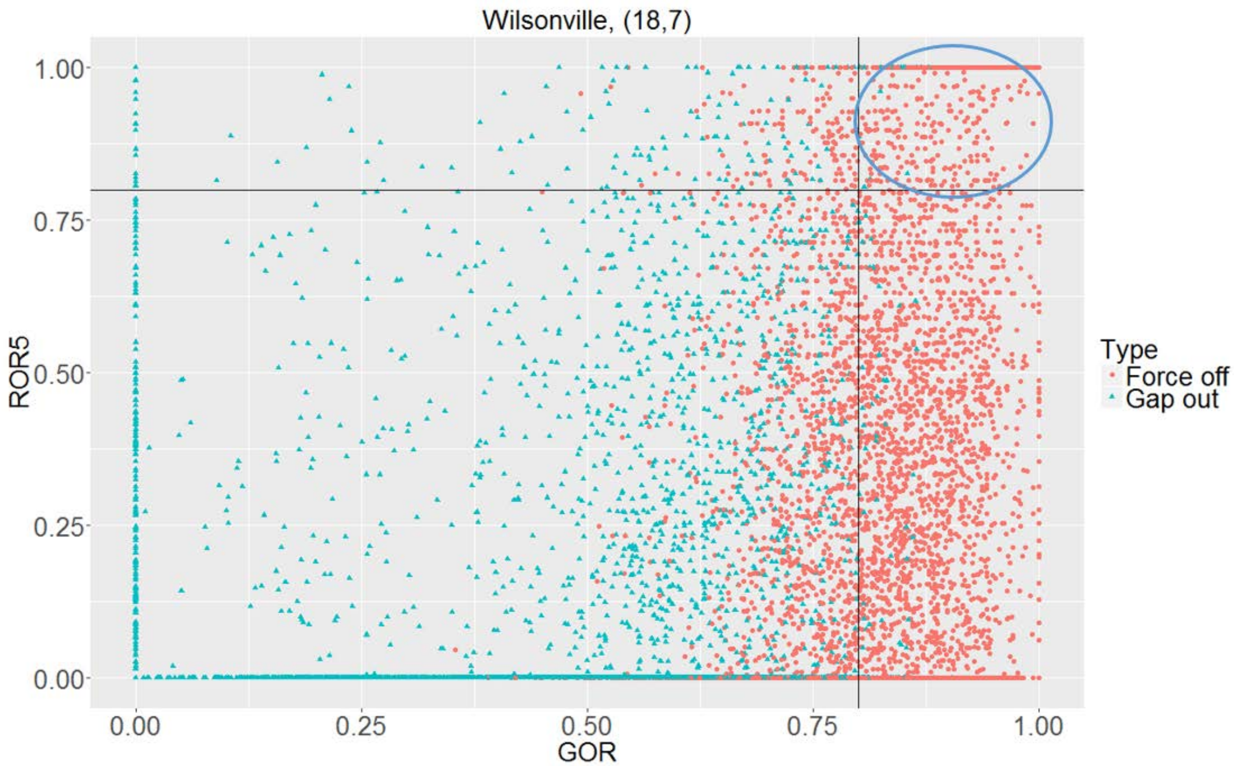


Figure 7.8: ROR_5 vs GOR of the loop sensor 18 at the Wilsonville intersection

If the video performance is comparable to loop performance, it is expected that the scatterplots of ROR_5 vs GOR will be similar to that of the loop sensors. The loop GOR vs loop ROR_5 and video GOR vs video ROR_5 of each pair of stop bar sensors are shown side by side in Figure 7.9.

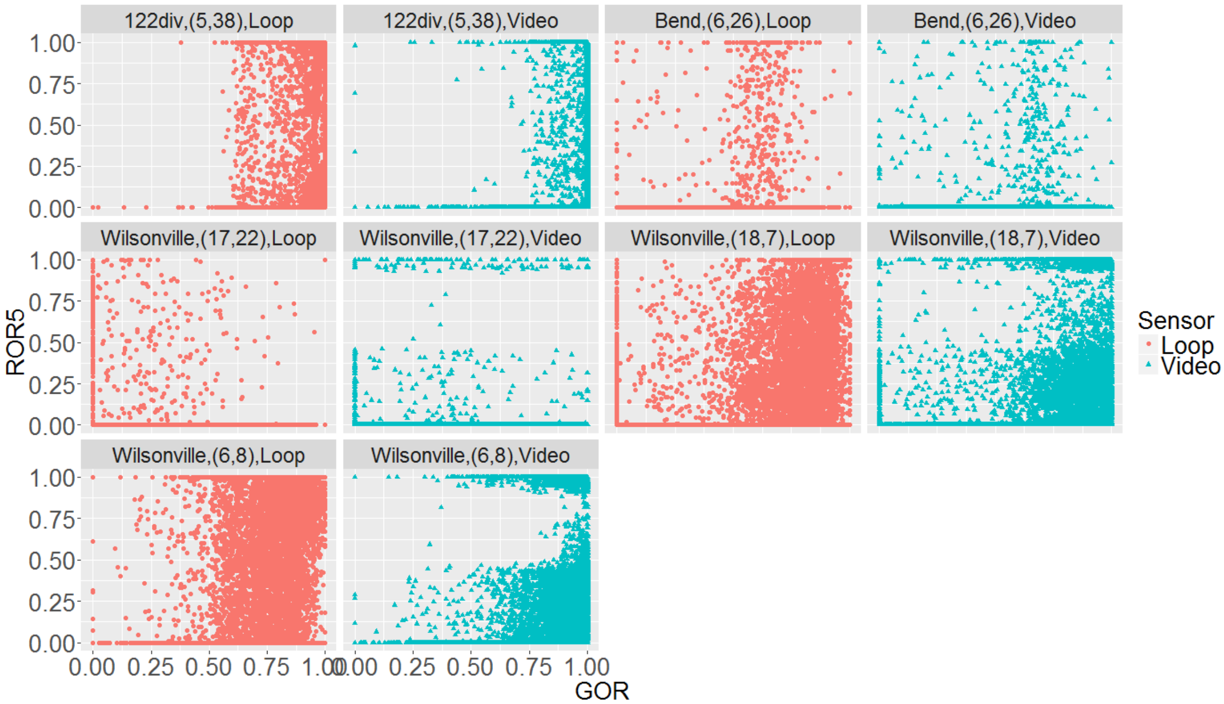


Figure 7.9: Loop GOR vs Loop ROR_5 and Video GOR vs Video ROR_5

It can be seen that the number of points on the right half of each subplot are much different for case of loop as compared to video, except for the Bend site, which doesn't seem to have to many split failure scenarios. In addition, for the sensors at the Wilsonville Rd & Town Center Loop West, it seems like the video sensors miss many data when the ROR_5 is between 0.5 and 1.0.

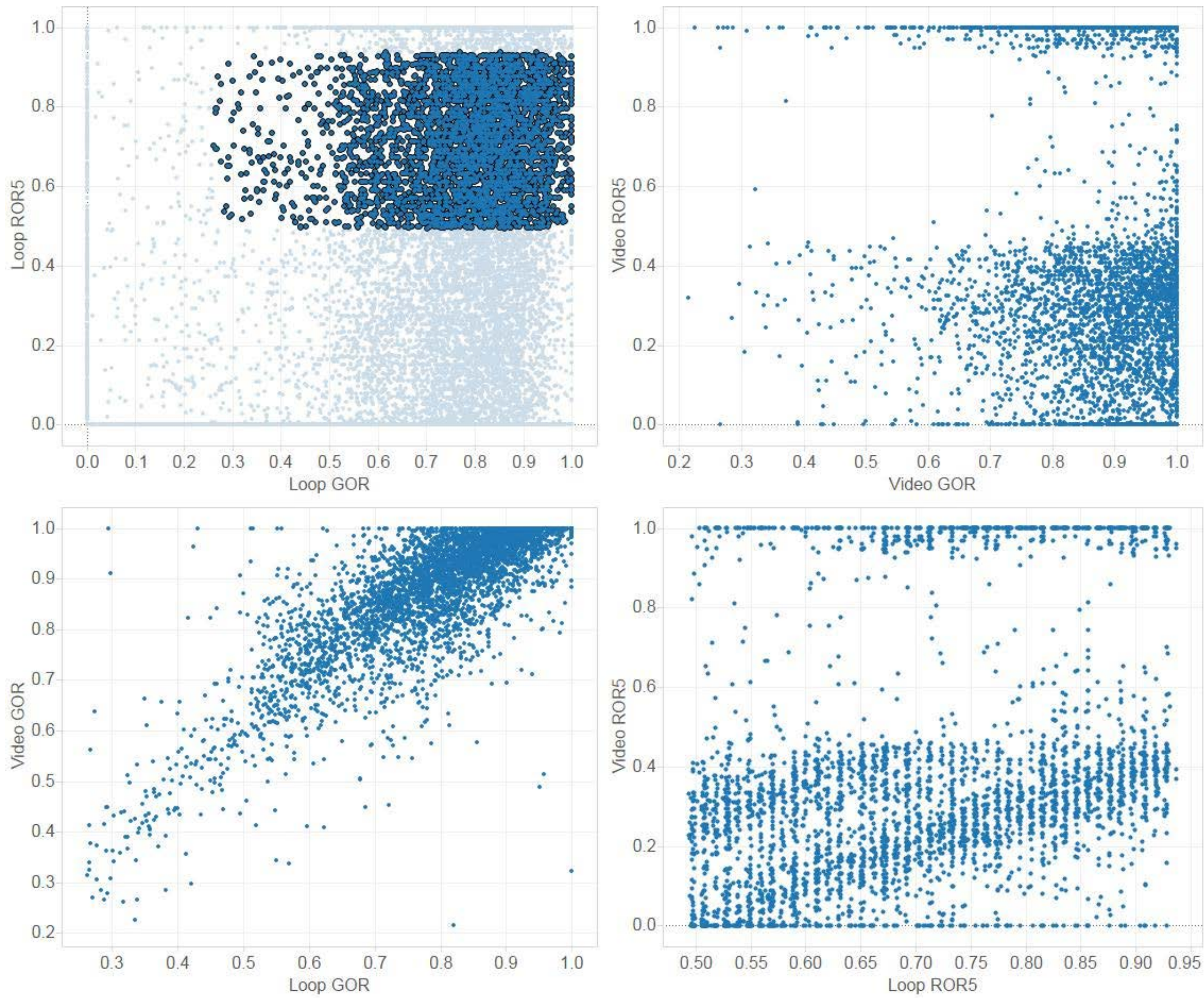


Figure 7.10: Distribution of the Data with ROR_5 being Between 0.5 and 1.0 at the Wilsonville Rd & Town Center Loop West

A further check to these data is shown in Figure 7.10. It can be found that the GORs of loop sensors and video sensors generally still show some linear trend (lower left vs. lower right). However, the ROR_5s of loop sensors and video sensors are completely unmatched (upper left and upper right). It can be seen that most video ROR_5s are lower than 0.5 and a few data are close to 1. This suggests that application of this metric would not produce usable results if video sensors were used.

Table 7.8 shows the number of split failures detected by each sensor. Video sensor 38, 22, and 7 overestimate split failures when compare to the loop sensors. Video sensors 8 and 26 underestimate the split failures when compared to the loop sensors.

Table 7.8: Number of Split Failures Detected by Each Sensor

Sensors	(5,38)	(6,26)	(17,22)	(18,7)	(6,8)
Loop	1865	10	2	583	1795
Video	4630	9	59	1013	1485
Ratio of video to loop	2.48	0.90	29.50	1.74	0.83

This summary is not surprising given the trends shown in Figure 7.10. Even though the GOR values of the two sensors show a relatively linear trend, the GOR_5 values which fall all over the board compromise the ability of the video sensor to detect a split failure.

7.4 SUMMARY

In this chapter, the performance of video sensors compared to inductive loops at the stop bar in determining the TTG in green time, the TFSC in red time, and the identification of a split failure using occupancy metrics was evaluated. Largely, the trends presented in this chapter were consistent with those identified in the advance detector analysis. Figure 7.11 and Figure 7.12 summarize the TTG and TFSC data, respectively, for the stop bar sensors analyzed in this work. Generally, TTG and TFSC had reasonable performance with several sensor pairs with normal data in the range of 90%, though there were sensor pairs which experienced normal data only 75%-80% of the time. For the occupancy related measure none of the sites had reasonable performance. This is consistent with the trend seen in occupancy measures for advanced detectors.

As was seen previously, there are site characteristics which impact the performance of these units, and while trends were identified, due to the limited amount of sensor pairs analyzed at any given site, additional data would be needed to generalize results. For TTG, the video sensors performance was consistent with the loops during very low volume and very high volume periods with decreased performance observed during moderate volumes, suggesting that video would perform well as a surrogate for loops in locations with these conditions. For TFSC, the video sensor was more consistent with the loop output when traffic volumes are higher. When placing a call at night, the temporal placement of the video call tends to differ much more than in the daytime. Given the results seen in this work, it would be reasonable to deploy video for stop bar detection with the knowledge that modest differences will occur, when compared to loops, for medium volume conditions. It is not recommended to deploy stop bar video for any occupancy related metric.

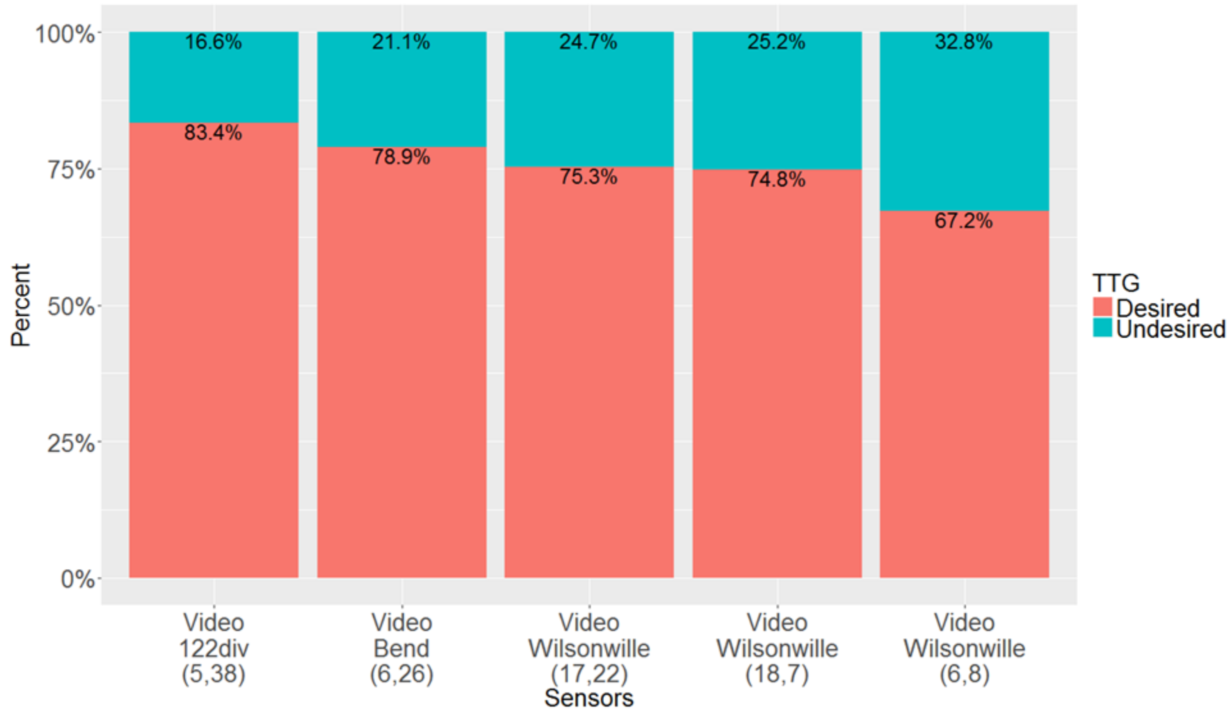


Figure 7.11: TTG data for stop bar sensors

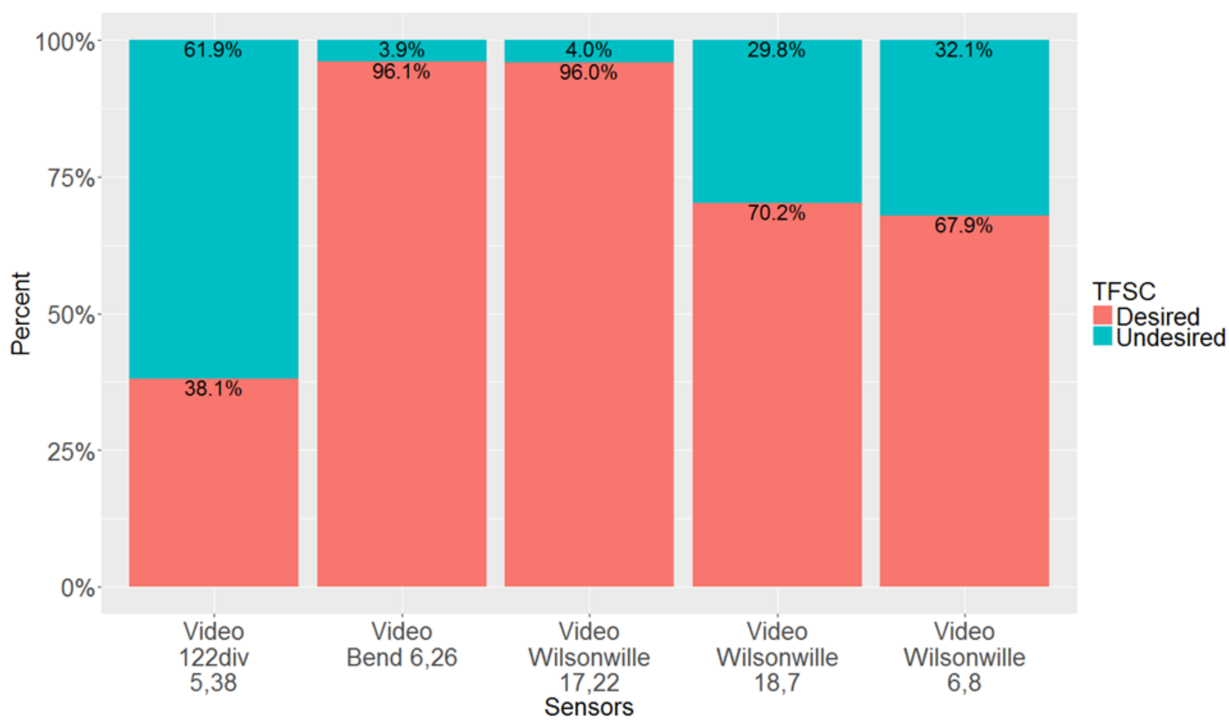


Figure 7.12: TFSC data for stop bar sensors

8.0 COST-BENEFIT ANALYSIS

Transitioning to an economic analysis of detection, this chapter will layout and conduct a Life Cycle Cost Analysis (LCCA) for various vehicle detection and adaptive control technologies. Technologies chosen for analysis are those currently used by ODOT, or those that represent a specific type of technology, based upon the availability of cost information, which was obtained through practitioner surveys and product manufacturer and vendor inquiries. Along with initial installation costs, costs associated with maintenance and troubleshooting were also collected from members of the TAC. These were combined in a manner which allowed for the construction of a LCCA tool using Microsoft Excel which calculates Life Cycle Costs for various alternatives. Additionally, the required savings of user costs for more expensive alternatives is calculated using methods and values from the American Association of State Highway and Transportation Officials (AASHTO) *User and Non-User Benefits Analysis for Highways*. Commonly referred to as the "Red Book", this publication provides benefits and costs values for highway and transportation projects.

8.1 SELECTION OF TECNOLOGIES FOR ANALYSIS

8.1.1 Adaptive Control Systems

As noted earlier in this document, adaptive systems use various combinations of volume, occupancy, and vehicle presence as inputs to their algorithms. For an economic analysis, it was deemed prudent to select systems that have been deployed within the state of Oregon. As such, this analysis looks at four ASCT technologies deployed within the state:

- Sydney Coordinated Adaptive Traffic System (SCATS)
- Trafficware SynchroGreen
- Rhythm Engineering InSync: Fusion
- Northwest Signal (Peek) Transcend

In addition to these systems, as a baseline measurement this research also included a traditional coordinated signal option for comparison.

8.1.2 Vehicle Detection

Adaptive systems rely heavily on detection to provide information for decision-making to accommodate real-time traffic conditions. Vendor specifications vary on the type of technology specified to develop this information. As such, through discussions with the TAC and other stakeholders as well as a search of offerings by various vendors, a comprehensive list of non-invasive detection devices was developed for analysis. Of these devices, cost information was procured for the following devices and will be included in the analysis.

- Inductive Loop Stop bar
- Inductive Loop Advanced
- Sensys Magnetometers
- Wavetronix SmartSensor Matrix (radar)
- Wavetronix SmartSensor Advanced (radar)
- Iteris VersiCam (video)
- Iteris Vantage Vector (hybrid radar and video)
- Traficon FLIR (thermal)

These detection technologies capture the four primary types of vehicle detection: inductive loops, video, radar, and thermal. Although not a comprehensive list of all available detection technologies and manufacturers, they encapsulate each type of detection and the cost range in which that type falls. In addition to the cost to purchase the physical detector, the LCCA includes the cost for detection cards required for the number of inputs necessary per approach. Although there are technical differences, it is presumed that the wiring cost is fairly consistent among each type of detection.

8.2 DETERMINATION OF COSTS

This section describes how the cost information for the components of the LCCA were gathered. The initial step in obtaining these costs was reaching out to manufacturers and ODOT officials through an informal survey. The second step was through direct email to the specific manufacturers and practitioners. A final attempt to capture pertinent cost information was made through using national institution forums such as the Institute of Transportation Engineers (ITE).

8.2.1 Signal Control

The following is a breakdown of the costs for each of the signal control technologies and the source of those costs. In order to allow the user to specify number of intersections in their analysis, the costs were converted to a per intersection basis and all ongoing costs were converted to an annual cost basis. Figure 8.1 shows an example of the questionnaire sent out to ASCT manufacturers and ODOT practitioners in attempt to obtain cost information for these signal control technologies.

Cost Item	Measurement
How much per intersection does the Software / Hardware Cost?	Per Intersection
Are there any additional costs per corridor for the Software / Hardware?	Per Corridor
How much does it cost the agency to maintain the system Annually?	System / Annually
Is there a server or central computing software that the agency needs to install at their TMC? If so, what is the cost associated with this?	Per
Recommended Mainline Stopbar Detection	Type
Recommended Mainline Advanced Detection	Type
Recommended Minor Stopbar Detection	Type
Recommended Minor Advanced Detection	Type
What other factors are required to maintain the system?	-----

Figure 8.1: Signal Timing Practitioner Questionnaire

In the following sections, the initial costs for each control type will be laid out, as well as the recommended detection layouts, which were gathered from manufacturer sources including direct contact, websites, and white papers. For this analysis it is presumed that when detection type is left unspecified, inductive loop detection is used.

8.2.1.1 Coordinated Signal Timing

Coordinated signal timing was included as a baseline measurement for the LCCA. Although coordinated signals do not qualify as an ASCT, this deployment is typically used before, or in opposition of, installation of an ASCT. According to the *National Traffic Signal Report Card: Technical Report 2005*, optimizing signal timing, or retiming, costs from $2,500 to $3,100 per signal per update. This range is based on data from six separate studies and uses three key components including traffic signal hardware, routing traffic signal timing updates, and maintenance performed by well-trained technicians *(Institute of Transportation Engineers 2005)*. The report goes on to state that routine traffic signal timing updates cost $3,000 per intersection and should be updated every three to five years. Additionally, in consideration of the date of this report and the effect of inflation, the costs associated with coordinated signal timing have been adjusted for 2016 prices using a government online inflation calculator *(Bureau of Labor Statistics 2016).* Therefore, the LCCA utilizes an initial cost per intersection for coordinated signal timing to be $3,760 and an annual maintenance cost of $1,200 ($3,600 / 3 years). There were no additional costs per intersection or server or central software costs associated with coordinated signal timing. The following is a breakdown of the costs captured for coordinated signal timing:

- Initial Coordinated Cost Per Intersection: $3,760
- Additional Coordinated Costs per Intersection: $0

- Annual Coordinated Maintenance Cost: $1,200
- Coordinated Server or Central Software Cost: $0

Figure 8.2 presents the recommended detection layout for coordinated signal timing according to the ODOT Traffic Signal Design Manual, comprised of inductive loops for all approaches for both stop bar and advanced detection *(ODOT Traffic Signal Standards Unit 2016).*

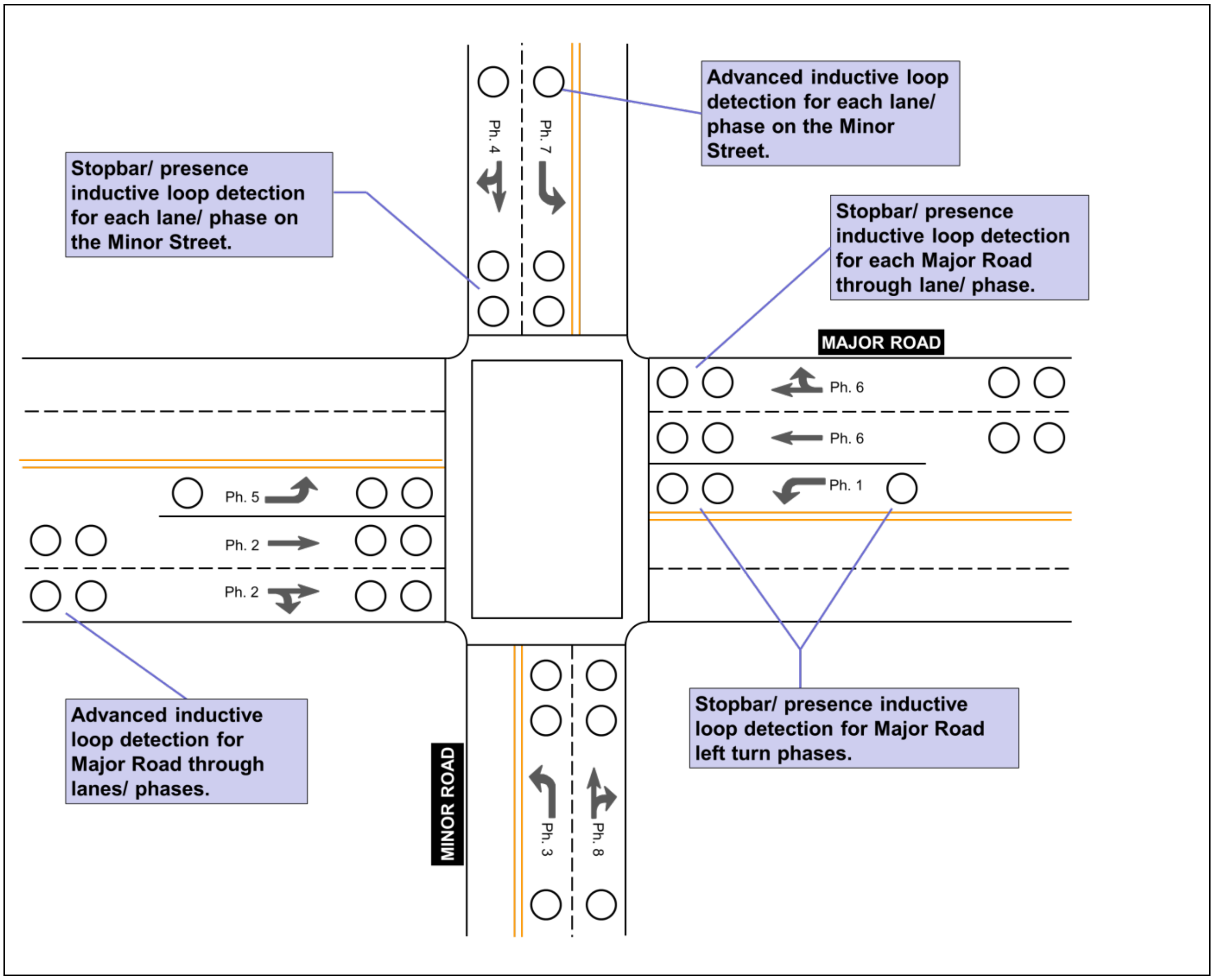


Figure 8.2: Coordinated signal timing recommended detection layout

8.2.1.2 Sydney Coordinated Adaptive Traffic System (SCATS)

Initially developed in Sydney, Australia, SCATS has been deployed worldwide. The cost information gathered for SCATS came from a United States Distributor. Although the distributor acknowledged that pricing SCATS on a per intersection basis was complicated, they quoted that typical initial projects are sized in the 15 intersection range and usually costs around $300,000. Therefore, the cost of $20,000 per intersection was used for the LCCA in this research. The SCATS software is licensed by the number of intersections and a server can handle up to 250 signals. Therefore, there were no identified additional cost per corridor as they are captured in the initial $20,000 per intersection cost. Additionally, software maintenance and support services range per customer depending on the size of the system, but typical costs are in the $10,000-$25,000 for annual maintenance for the system. The LCCA tool uses the average, $17,500, for the annual maintenance cost for SCATS (this is an annual fee to adjust operational parameters to current demand levels). The SCATS central software costs range depending on the size of the system. To capture this range, the central software costs were captured in the $20,000 per intersection cost stated previously for the initial cost. The following is a breakdown of the costs captured for SCATS:

- Initial SCATS Cost Per Intersection: $20,000
- Additional SCATS Costs per Intersection: $0 (captured in initial cost)
- Annual SCATS Maintenance Cost: $17,500 / # of intersections
- SCATS Server or Central Software Cost: $0 (captured in initial cost)

The recommended detection layout for SCATS was taken from *An Introduction to the New Generation SCATS 6* white paper provided through the SCATS website. Shown in Figure 8.3, the white paper recommends SCATS only requires stop bar detection on all approaches *(NSW Government 2015)*. When installed in Bend, OR, ODOT also installed advance detection for dilemma zone protection.

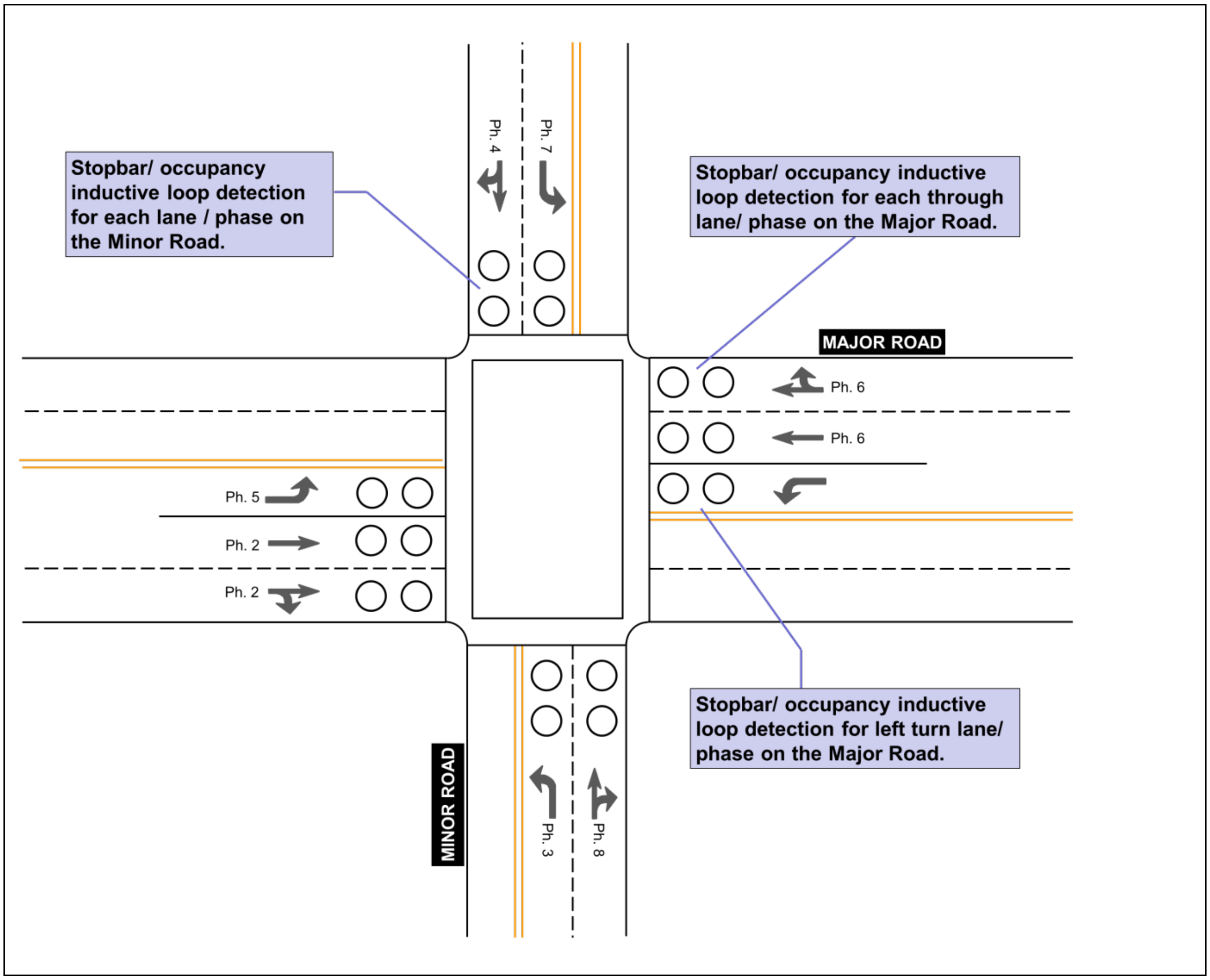


Figure 8.3: SCATS recommended detection layout

8.2.1.3 Trafficware SynchroGreen

As cost information for Trafficware's ASCT product SynchroGreen was not available from the vendor, it was gathered from the consulting community, specifically Dave Bruggeman, PE, PTOE, and Bruce Dressel, PE, who have experience designing and employing this ASCT technology *(Dressel and Bruggeman 2016*. The initial base cost per intersection to deploy SynchroGreen was quoted at $13,500. Additionally, the server, training, and setup is estimated to be $20,000. This number encompasses all the additional per intersection costs and annual maintenance costs (training) associated with SynchroGreen. No additional hardware is required beyond costs associated with incompatible controller replacement (for this analysis, it is presume that the existing controllers are compatible). The following is a breakdown of the costs captured for SynchroGreen:

- Initial SynchroGreen Cost Per Intersection: $13,500
- Additional SynchroGreen Costs per Intersection: $0 (captured in server cost)

- Annual SynchroGreen Maintenance Cost: $0 (captured in server cost)
- SynchroGreen Server or Central Software Cost: $20,000

The recommended detection configuration for SynchroGreen was determined from Trafficware's *SynchroGreen Technical White Paper*. According to the white paper, SynchroGreen utilizes any non-proprietary technology (i.e. inductive loops, video, wireless, advanced radar, etc.) and multiple technologies can be used on the same system *(Traffic Ware 2012)*. As shown in Figure 8.4, SynchroGreen requires stop bar detection on all approaches and advanced detection on major through lanes.

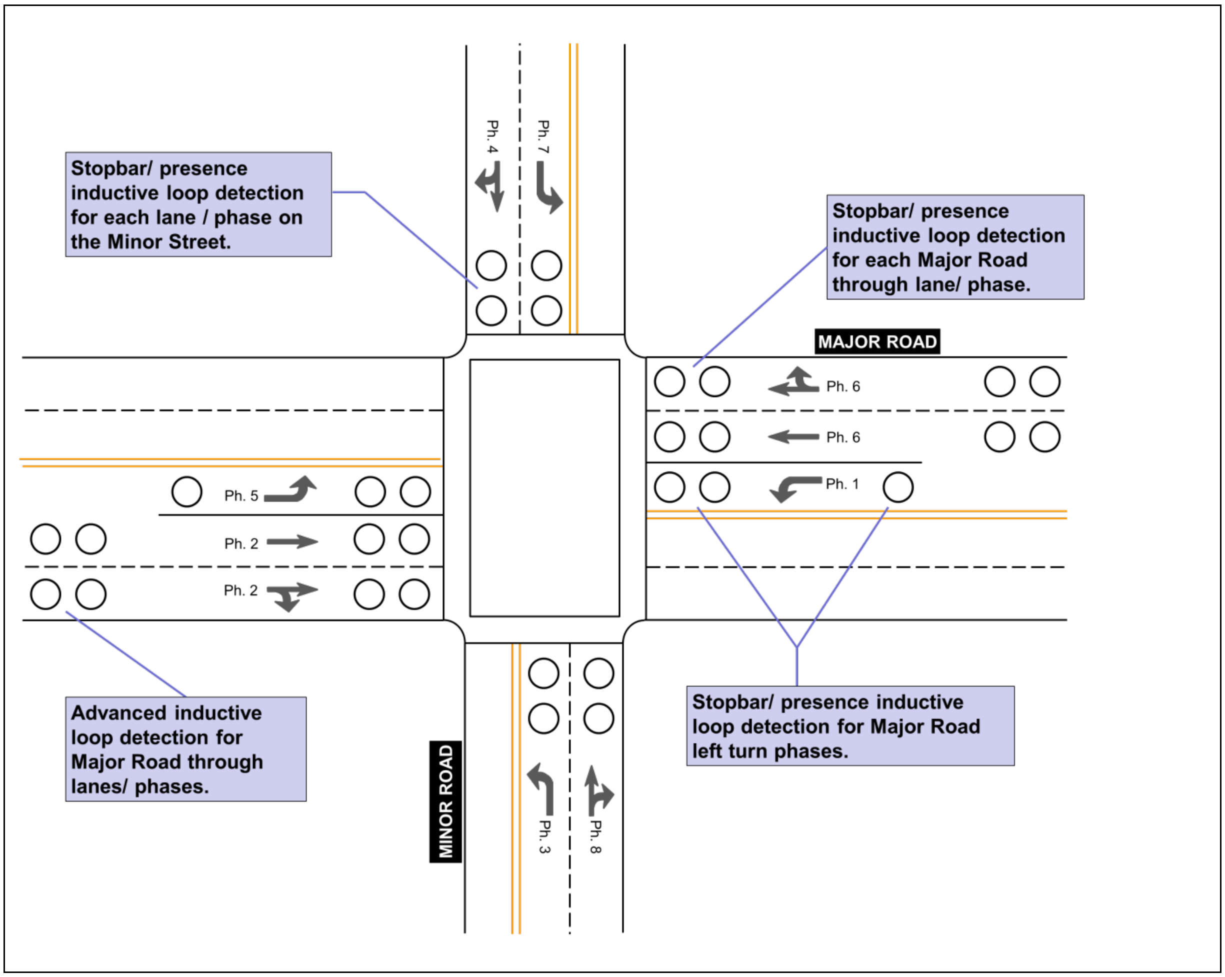


Figure 8.4: SynchroGreen recommended detection layout

8.2.1.4 Rhythm Engineering InSync: Fusion

Developed by Rhythm Engineering, InSync: Fusion has been on the market since 2008. This cost information was acquired directly from an employee of Rhythm Engineering. The InSync base model adaptive traffic control system includes a processor, video detection system, and all hardware and is quoted to be $25,000. However, the InSync: Fusion module allows the agency to utilize their existing detection including loops, radar, video, etc. Therefore, the InSync: Fusion module was chosen for the LCCA evaluation so the user can specify which type of detection to utilize. The InSync: Fusion module was quoted as $5,000 per intersection plus an additional $5,000 for the pedestrian module. This equates to an initial per intersection cost for InSync of $10,000. Additional costs per intersection include project management costs of $2,750 for adaptive configuration preparation, installation training, deployment and monitoring. Annual maintenance costs are minimal and depend on the level of attention the agency desires to give to the system. Quoted as a "plug-and-play" technology, the only annual maintenance costs are $750 per intersection for warranty services. InSync does not need a central server as the system includes a processor in each cabinet that serves as a distributed architecture and intelligence. The following is a breakdown of the costs captured for InSync: Fusion:

- Initial InSync: Fusion Cost Per Intersection: $10,000
- Additional InSync: Fusion Costs per Intersection: $2,750
- Annual InSync: Fusion Maintenance Cost: $750
- InSync: Fusion Server or Central Software Cost: $0

The recommended detection configuration for InSync: Fusion was determined from *InSync White Paper*. As seen in Figure 8.5, this adaptive system utilizes stop bar detection on all approaches which can be any form of detection (inductive loops, radar or magnetometers).

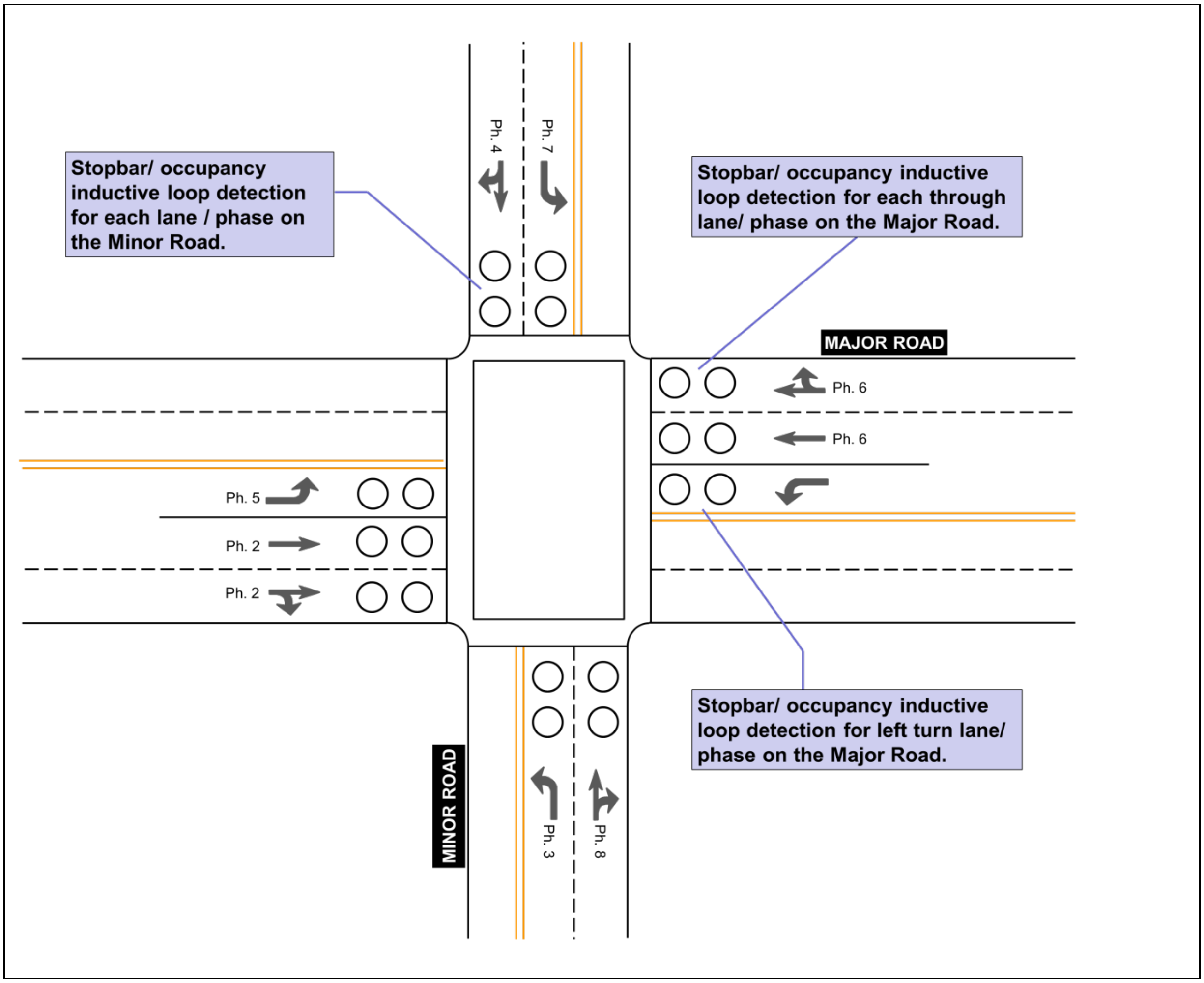


Figure 8.5: InSync: Fusion recommended detection layout

8.2.1.5 Northwest Signal Transcend

The cost information acquired for Transcend came from an employee of Peek Traffic (Peek recently acquired Northwest Signal). Transcend requires research to be completed on the corridor before the system is deployed, including current count data for all intersections, so that new timing and coordination plans can be created and implemented for the proper operation of Transcend. All costs including maintenance, additional costs, and central server costs were estimated to be in the $30,000 to $40,000 range. Therefore, the average cost of $35,000 per intersection for all pertaining costs was used to conduct the LCCA including updating controller software to the Voyage platform. The following is a breakdown of the costs captured for Transcend:

- Initial Transcend Cost Per Intersection: $35,000
- Additional Transcend Costs per Intersection: $0 (captured in initial cost)
- Annual Transcend Maintenance Cost: $0 (captured in initial cost)

- Transcend Server or Central Software Cost: $0 (captured in initial cost)

The recommended detection layout for Transcend was determined from Northwest Signal's Brochure on Transcend. As seen in Figure 8.6, Transcend requires advanced detection to count vehicles and hold presence in addition to normal call/extend detection at the stop bar *(Northwest Signal n.d.)*.

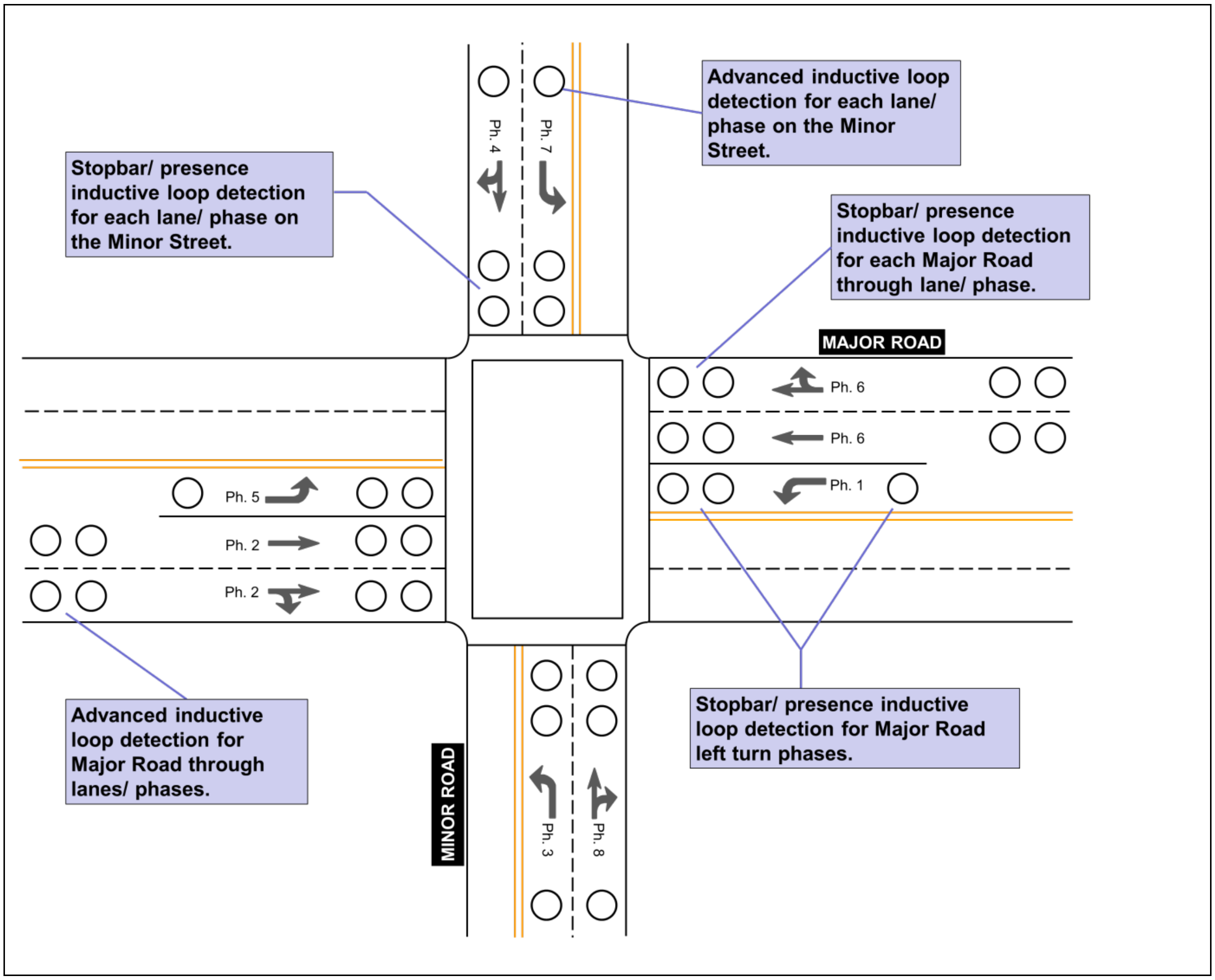


Figure 8.6: Transcend recommended detection layout

8.2.2 Vehicle Detection Costs

The following is a breakdown of the costs for each of the vehicle detection costs and the source of those costs. In order to allow the user to specify the detection by location (stop bar or advanced) and approach (major or minor road) the detection costs are broken down by approach. Figure 8.7 shows an example of the questionnaire sent out to detection vendors and ODOT practitioners in attempt to obtain cost information for various vehicle detection technologies. This section breaks down the costs per approach for each type of vehicle detection.

Cost Item	Measurement
What is the total cost for purchasing and installing each detector (including all components) during new construction or intersection rehabilitation?	Per Detector
How many maintenance visits per year are typically required to maintain this detection, and what is the estimated cost of each visit?	Per Detector
How many troubleshooting visits per year are required to maintain this detection, and what is the estimated cost of each visit?	Annually / Unit
What is the lifespan of this detection?	Months or Years / Unit
What type of traffic control is typically required when replacing or performing maintenance on this detection? (i.e. 1 lane vs 2 lane, etc.)	-----
What is the typical cost for traffic control when this detection needs to be maintained or replaced?	Per Detector

Figure 8.7: Vehicle Detection Practitioner Questionnaire

8.2.2.1 Inductive Loop: Stop Bar and Advanced

Inductive loops are an invasive detection technology that require placement in the traffic lane. Figure 8.8 shows an example detection layout for both stop bar and advanced inductive loop detection for Major Road and Minor Road approaches. Cost and maintenance information for inductive loop detections, shown in Table 8.1, were provided by a member of the project technical advisory committee (TAC). The lifespan of an inductive loop detector was noted to be 15 years. Also, inductive loops do not have any associated annual maintenance costs as they do not require cleaning, firmware/software updates, adjustments, or troubleshooting, nor do they have any salvage value. Therefore, the annual maintenance cost associated with loop detectors within a 10-year analysis period is $0.

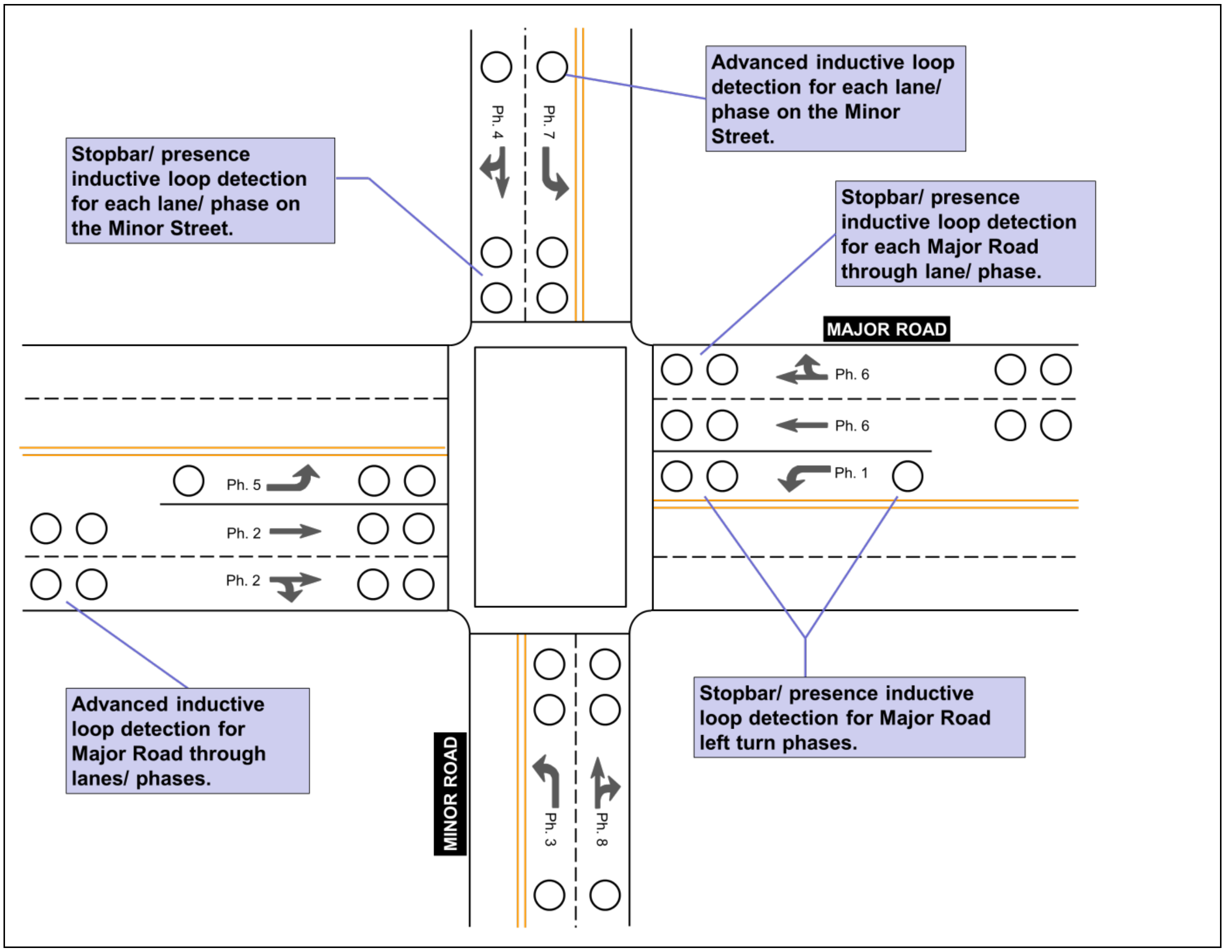


Figure 8.8: Inductive loop detection layouts for both stop bar and advanced detection for Major Road and Minor Road approaches

Table 8.1: Inductive Loop Detection Costs

Inductive Loop Detection Purchase	$600	
Inductive Loop Detection Channels	2 channels	$150 / card
Major Stop bar Detectors / Approach Detection Cost	7	$4,800
Minor Stop bar Detectors / Approach Detection Cost	4	$2,700
Major Advanced Detectors / Approach Detection Cost	2	$1,350
Minor Advanced Detectors / Approach Detection Cost	2	$1,350
Estimated Lifespan of Detection	15 years	
Annual Maintenance Visits / Cost per Approach	None	$0.00
Traffic Control Maintenance / Cost per Approach	None	$0.00

8.2.2.2 Sensys Magnetometers: Stop Bar and Advanced

Sensys Magnetometers are wireless invasive detection technology that detect vehicles by magnetic disturbances. Figure 8.9 shows an example detection layout for Sensys magnetometers. The costs associated with Sensys Magnetometers, shown in Table 8.2, were provided by a member of the project technical advisory committee (TAC) in the form of an engineer's estimate from a supplier. According to Sensys Networks, their Magnetometers typically have a life span of 8.5 years as their batteries require replacement *(Sensys Networks 2008)*. Temporary traffic control for replacement was estimated to cost $1,000 for a simple intersection (portable signs and setup cost) and $2,500 for a complex intersection ($1000 + 4 flaggers x 8hrs/flagger + $45/hour). For this analysis traffic control was estimated to be the average of the two intersection types at $1,750. Therefore, the traffic control cost required when replacing these units at the end of life is estimated to $437.50/approach. There are no annual maintenance costs associated with Sensys Magnetometers.

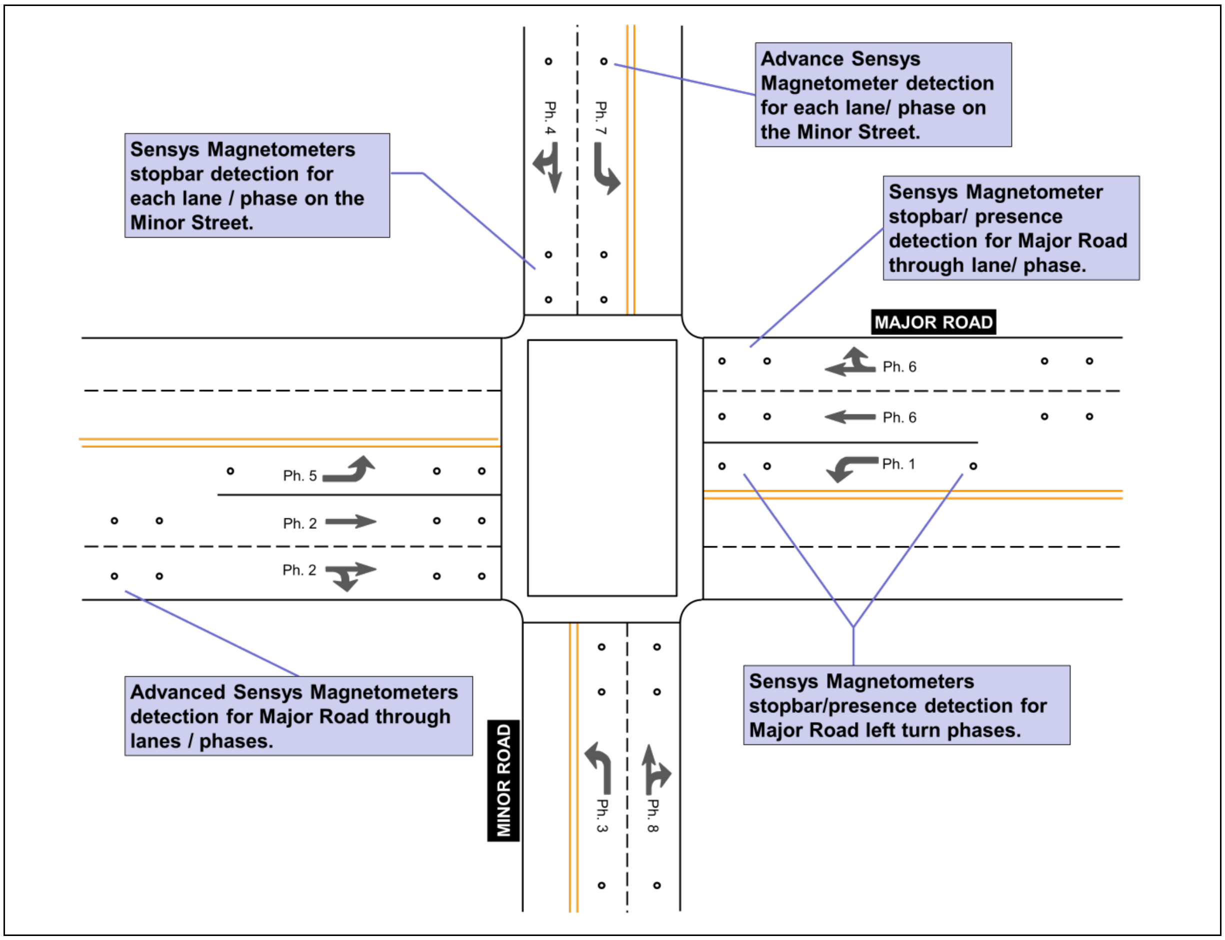


Figure 8.9: Sensys Magnetometers detection layouts for both stop bar and advanced detection for Major Road and Minor Road approaches

Table 8.2: Sensys Magnetometers Detection Costs

Sensys Magnetometer Detection Purchase	$550	
Sensys Magnetometer Detection Channels	4 channels	$525 / card
Other Costs: Wireless Access Point	$5000 / Intersection	
Major Stop Bar Detectors / Approach Detection Cost	7	$6,150
Minor Stop Bar Detectors / Approach Detection Cost	4	$3,975
Major Advanced Detectors / Approach Detection Cost	2	$2,875
Minor Advanced Detectors / Approach Detection Cost	2	$2,875
Estimated Lifespan of Detection	8.5 years	
Annual Maintenance Visits / Cost per Approach	None	$0.00
Traffic Control Maintenance for Replacement at End of Life Span / Cost per Approach	1 lane	$437.50

8.2.2.3 Wavetronix: SmartSensor Matrix/SmartSensor Advance

The SmartSensor Matrix is a stop bar radar detector while the SmartSensor Advanced is an advanced detector, and they will serve as the radar technology for this cost analysis. Figure 8.10 shows example SmartSensor Matrix and SmartSensor Advance layouts for both stop bar and advanced detection for Major Road and Minor Road approaches. The costs associated with Wavetronix Radar products, shown in Table 8.3, were acquired directly from a Wavetronix employee.

Radar maintenance costs were obtained from a TAC member with a lifespan of a Wavetronix Radar unit reported to be about 10 years. SmartSensor Matrix stop bar detectors and SmartSensor Matrix Advanced detectors maintenance cost were reported to be equivalent. Radars do not require cleaning and therefore have no associated cleaning cost. Their firmware and/or software needs to be updated approximately every three years which requires four hours of labor with bucket truck for an approximate cost of $400 / 3 years, or an annual cost of $133. Additionally, the physical radar units need to be adjusted and/or require troubleshooting on a yearly basis which also requires 4 hours labor and is equivalent to an annual cost of $400. Together, the annual cost for one radar unit on a per approach basis is $133.25 ($533 per intersection / 4 approaches). Additionally, the traffic control required for each approach is $437.50 ($1,750 for intersection/ 4 approaches) annually. Therefore, the total annual maintenance cost per approach for the SmartSensor Matrix and Advance is $570.75 per detector.

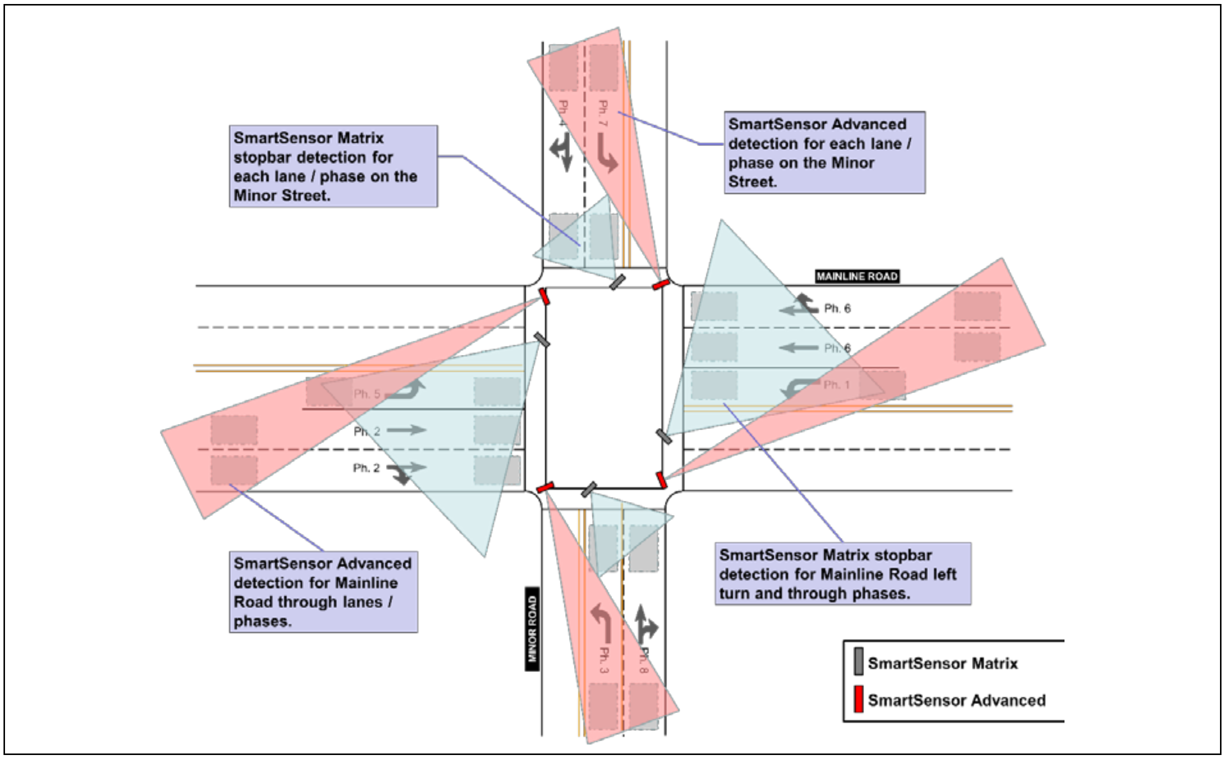


Figure 8.10: Wavetronix radar detection layouts for both stop bar and advanced detection for Major Road and Minor Road approaches

Table 8.3: Wavetronix Radar Detection Costs

Wavetronix Radar Stop Bar Detection Purchase	$5000	
Wavetronix Radar Advanced Detection Purchase	$5950	
Wavetronix Radar Stop Bar Detection Channels	4 channels	$350 / card
Wavetronix Radar Advanced Detection Channels	2 channels	$330 / card
Major Stop Bar Detectors / Approach Detection Cost	1	$5,350
Minor Stop Bar Detectors / Approach Detection Cost	1	$5,330
Major Advanced Detectors / Approach Detection Cost	1	$6,280
Minor Advanced Detectors / Approach Detection Cost	1	$6,280
Estimated Lifespan of Detection	10 years	
Annual Maintenance Visits / Cost per Approach	1	$133.25
Traffic Control Maintenance / Cost per Approach	1 lane	$437.50

8.2.2.4 Iteris VersiCam Video Stop Bar Detection

The Iteris Vantage Vector is a video detector that can detect the presence of vehicles at the stop bar for smaller intersections. This detector is not intended to be used for advanced detection when mounted at the stop bar, but can be used if mounted close to the advanced detection zone . Figure 8.11 shows the layouts for stop bar Iteris VersiCam detection for Major Road and Minor Road approaches. The costs associated with Iteris VersiCam, shown in Table 8.4, were provided by a member of the project TAC in the form of an engineer's estimate from a supplier.

Video maintenance costs were also obtained from a TAC member, and the lifespan of an Iteris VersiCam unit was reported to be around 10 years. Video detector lenses need to be cleaned every two years on average which requires two labor hours and a bucket truck at a cost of $200 per visit, or an annual cost of $100. Their firmware and/or software needs to be updated approximately every three years which requires four hours of labor with bucket truck for an approximate cost of $400 / 3 years, or an annual cost of $133. Additionally, the physical video units need to be adjusted and/or require troubleshooting on a yearly basis which also requires 4 hours labor and is equivalent to an annual cost of $400. Together, the annual cost for one video unit on a per approach basis is $158.25 ($633 per intersection / 4 approaches). The traffic control for each approach during maintenance requires a one lane shutdown and costs $437.50 ($1,750 for intersection/ 4 approaches) annually. Therefore, the total annual maintenance cost per approach for the Iteris VersiCam is $595.75 per detector.

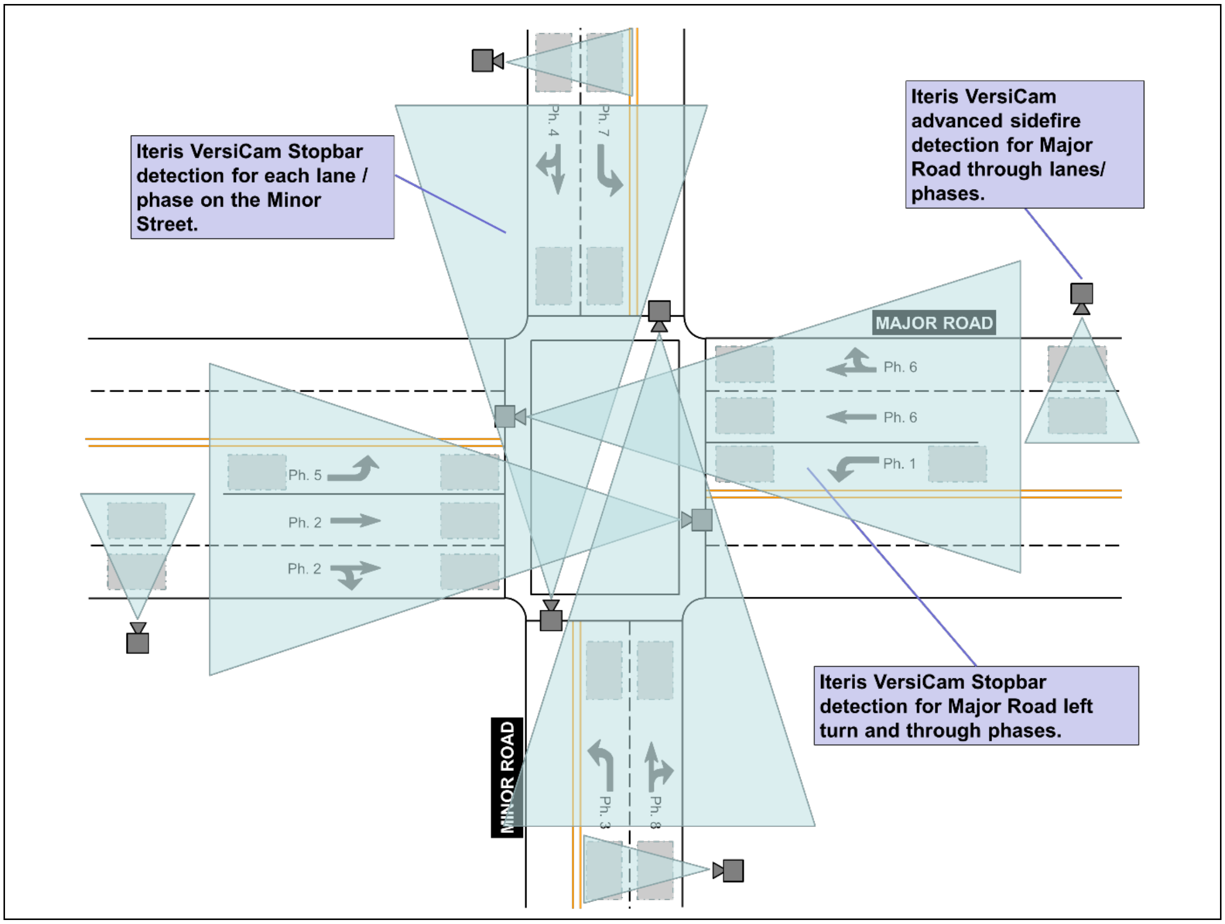


Figure 8.11: Iteris VersiCam video detector layouts for stop bar detection for Major Road and Minor Road approaches

Table 8.4: Iteris VersiCam Radar Detection Costs

Iteris VersiCam Stop Bar Detection Purchase	$3,000	
Iteris VersiCam Stop Bar Detection Channels	4 channels	$3000
Iteris VersiCam Advanced Detection Channels	2 channels	$1,500
Major Stop Bar Detectors / Approach Detection Cost	1	$6,000
Minor Stop Bar Detectors / Approach Detection Cost	1	$6,000
Major Advanced Detectors / Approach Detection Cost	1	$4,500
Minor Advanced Detectors / Approach Detection Cost	1	$4,500
Estimated Lifespan of Detection	10 years	
Annual Maintenance Visits / Cost per Approach	1	$158.25
Traffic Control Maintenance / Cost per Approach	1 lane	$437.50

8.2.2.5 Traficon FLIR Thermal Detector

The Traficon FLIR is a detector that uses thermal imaging to detect vehicles at the stop bar and advanced detection zones. Figure 8.12 shows the layouts for Traficon FLIR thermal detection for Major Road and Minor Road approaches. The costs associated with Traficon FLIR Thermal Detector, shown in Table 8.5, were provided by a member of the project technical advisory committee (TAC) in the form of an engineer’s estimate from a supplier. Thermal Detectors require the same annual maintenance as video detection, and therefore the costs are the same as for Iteris VersiCam.

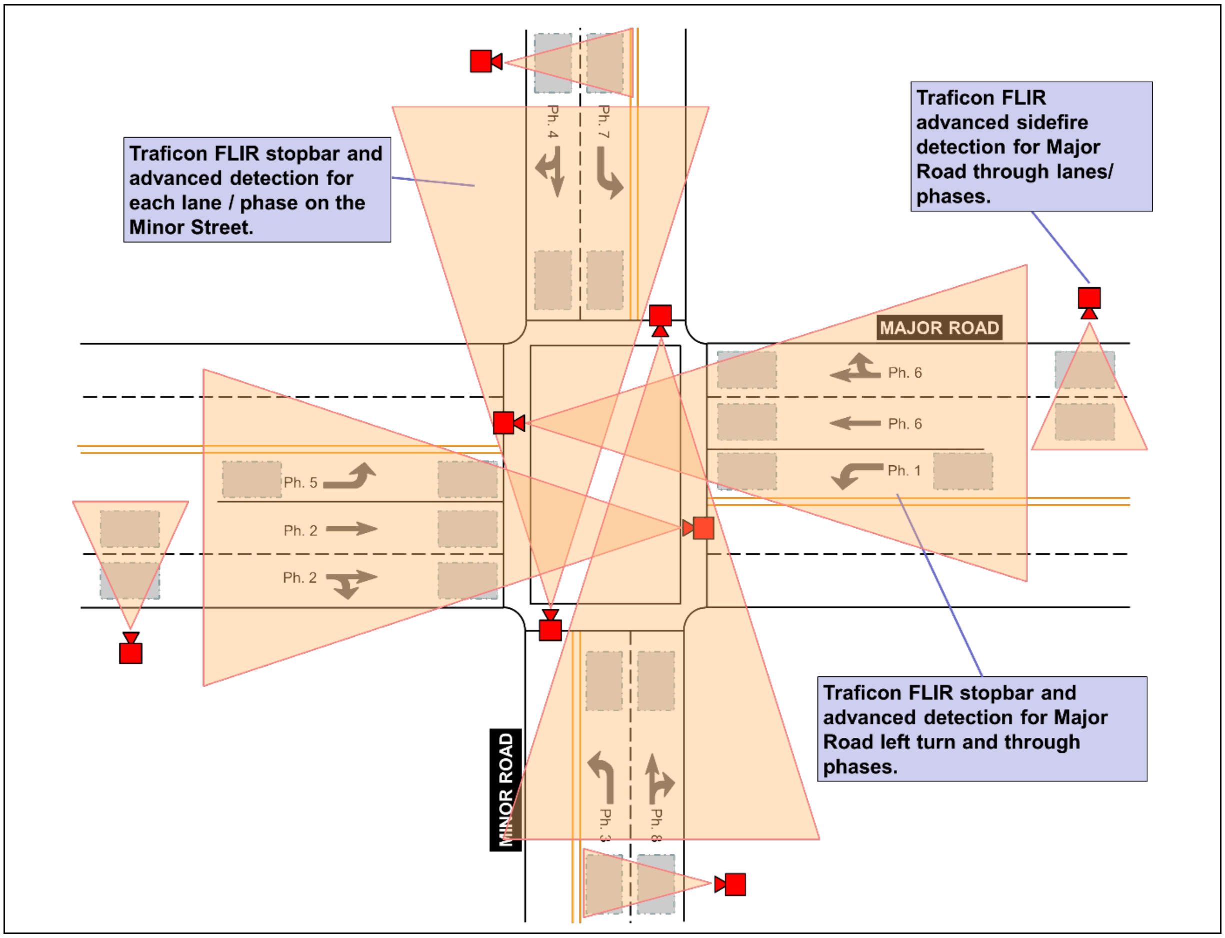


Figure 8.12: Traficon FLIR thermal detector layout for stop bar and advanced detection for Major Road and Minor Road approaches

Table 8.5: Traficon FLIR Thermal Detection Costs

Traficon FLIR Detection Purchase	$3,538	
Traficon FLIR Stop Bar Detection Channels	4 channels	$4,010
Traficon FLIR Advanced Detection Channels	2 channels	$2,610
Major Stop Bar Detectors / Approach Detection Cost	1	$7,548
Minor Stop Bar Detectors / Approach Detection Cost	1	$6,148
Major Advanced Detectors / Approach Detection Cost	1	$6,148
Minor Advanced Detectors / Approach Detection Cost	1	$6,148
Estimated Lifespan of Detection	10 years	
Annual Maintenance Visits / Cost per Approach	1	$158.25
Traffic Control Maintenance / Cost per Approach	1 lane	$437.50

8.2.2.6 Iteris Vantage Vector Hybrid Detector

The Iteris Vantage Vector Hybrid Detector has both a video detector and radar detector in the same unit. Figure 8.12 shows the layouts for Vantage Vector hybrid detectors for Major Road and Minor Road approaches. As seen in the figure, the Vantage Vector uses video imaging for stop bar detection and radar scanning for advanced detection. The hybrid detector is able to capture both zones using a single detector unit and two separate detector channel cards for stop bar and advanced detection. The costs associated with Iteris Vantage Vector, shown in Table 8.6, were provided by a member of the project technical advisory committee (TAC). Vantage Vector detector maintenance costs were presumed to be equivalent to maintaining one video detector with the addition of extra radar detection adjustments and troubleshooting costs. The lifespan of a Vantage Vector unit is purported to be around 10 years, and therefore does not require replacement within the analysis time period. Vantage Vector lenses need to be cleaned every two years on average which requires two labor hours and a bucket truck at a cost of $200 per visit, or an annual cost of $100. Their firmware and/or software needs to be updated approximately every three years which requires four hours of labor with bucket truck for an approximate cost of $800 / 3 years, or an annual cost of $266.67. Additionally, both the camera and radar components within the Vantage Vector unit need to be adjusted and/or require troubleshooting on a yearly basis which also requires 4 hours labor and is equivalent to an annual cost of $800 for an entire intersection ($400 per unit component). Together, the annual cost for one Vantage Vector unit on a per approach basis is $291.67 ($1166.67 per intersection / 4 approaches). Additionally, the traffic control for each approach during maintenance requires a one lane shutdown and costs $437.50 ($1,750 for intersection/ 4 approaches) annually. Therefore, the total annual maintenance cost per approach for the Iteris Vantage Vector Hybrid unit is $729.17 per detector.

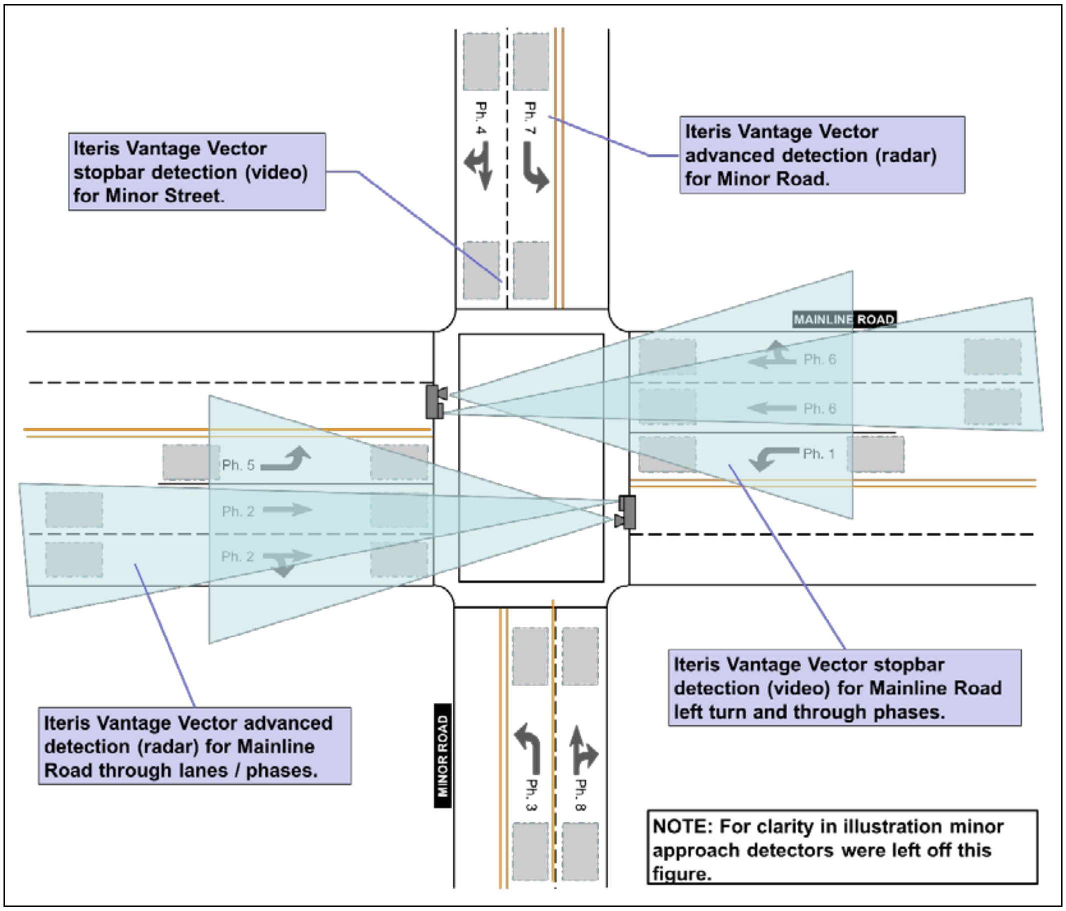


Figure 8.13: Iteris Vantage Vector hybrid detector layout for stop bar and advanced detection for Major Road and Minor Road approaches

Table 8.6: Iteris Vantage Vector Hybrid Detection Costs

Iteris Vantage Vector Detection Purchase	$5,880	
Iteris Vantage Vector Detection Channels	4 channels	$1000
Major Stop Bar Detectors / Approach Detection Cost	1	$6,880
Minor Stop Bar Detectors / Approach Detection Cost	1	$6,880
Major Advanced Detectors / Approach Detection Cost	1	$1,000
Minor Advanced Detectors / Approach Detection Cost	1	$1,000
Estimated Lifespan of Detection	10 years	
Annual Maintenance Visits / Cost per Approach	1	$291.67
Traffic Control Maintenance / Cost per Approach	1 lane	$437.50

8.2.3 Cost Summary

This section provided costs for every component used to carry out the LCCA including signal control technologies and various vehicle detection technologies. In addition, the source of each cost was listed and the methodology as to how each cost was broken down into an annual cost equivalent was presented. The vehicle detection technologies were broken down on a per approach basis with per approach maintenance and troubleshooting costs presented in an annualized format.

8.3 LIFE CYCLE COST ANALYSIS DOCUMENTATION

To conduct the analysis, a tool was developed using Microsoft Excel with the end goal of allowing a user to select and compare various signal control and detection alternatives (referred to as Life Cycle Cost Analysis Tool, or LCCAT). The LCCAT evaluates alternatives on a net present basis and converts all future annual and replacement costs to present value. For outputs, the LCCAT provides a life cycle cost analysis summary of deployment costs and resulting equivalent user costs. This section describes the mathematical formulas used in the LCCAT; documentation for the LCCAT will be provided under separate cover.

8.3.1 Analysis Inputs and Calculations

This section will discuss values presumed and calculated during the LCCA.

8.3.1.1 Discount Rate

. According to the AASHTO User and Non-User Benefit Analysis for Highways Red Book, if the analysis is measuring all costs and benefits in constant (inflation-removed) dollars a discount rate of 3% should be used*(American Association of State Highway and Transportation Officials 2010)*. Therefore, 3% is the default real discount rate in the LCCAT.

8.3.1.2 Analysis Period

While analyses are conducted across various time periods, the majority of comparisons use a 10-year analysis period. During conversations with TAC members regarding operation and maintenance factors of various detection and control technologies, the value of 10 years was fairly common in the expected lifespan of detection, in that given technological process, it’s not unexpected that detection would be replaced in about 10 years with a newer product, or that failure would require replacement in that general timeframe. As such, a 10-year analysis period was selected for the majority of comparisons.

8.3.1.3 Intersection Configuration

For all analyses, the intersection configuration consists of a four leg symmetrical intersection, with three lanes on the major street (two through, and one left turn) and two lanes on the minor street (one shared through-right, and one left turn). This analysis assumes that each intersection included in the signal control system has identical geometry and number of lanes per approach.

8.3.1.4 Life Cycle Cost Calculations

The analysis compares the life cycle costs of the selected alternatives based on total initial costs, total present annual costs, and total present replacement costs. Taken from the book *Engineering Fundamentals*, the LCCA uses basic engineering economic equations to discount annual maintenance and future replacement costs *(Moaveni 2005)*:

Equation 3: Present Value Annual Cost (PVAC)

$$(\boldsymbol{P/A,i,n}) = \boldsymbol{A} \times \frac{(\boldsymbol{1+i})^{\boldsymbol{n}} - \boldsymbol{1}}{\boldsymbol{i}(\boldsymbol{1+i})^{\boldsymbol{n}}}$$

Equation 4: Present Value Future Cost (PVFC)

$$(\boldsymbol{P/F,i,n}) = \boldsymbol{F} \times \frac{\boldsymbol{1}}{(\boldsymbol{1+i})^{\boldsymbol{n}}}$$

Equation 5: Total Present Life Cycle Cost

$$Total\ Present\ Life\ Cycle\ Value = IC + PVAC + PVFC$$

Where:

- IC = Initial cost
- P = Present Value
- A = Annual Payment
- F = Future Payment
- i = discount rate
- n = number of years in analysis period

Equation 3 and Equation 4 are used to calculate the present value of annual and future costs, respectively, and Equation 5 sums those values with the initial costs for a total present value of costs. This was done for ease of calculation within the spreadsheet tool used to run the comparative analysis. All costs presented in Section 8.2 are applied within the context of these three equations to provide a comparative analysis between various scenarios.

8.3.2 Life Cycle Cost Analysis Outputs

Output of the LCCA are presented in various forms for analysis. Formats and calculations used for this will be explained in this section.

8.3.2.1 *Summary Outputs*

Figure 8.14 shows an example summary of a LCCA output developed for this work. This format, along with numerical summary tables will be used for comparison of the differences between alternatives. Figure 8.14 allows the alternatives analyzed to be viewed in a side-by-side fashion including all three components which make up the total cost.

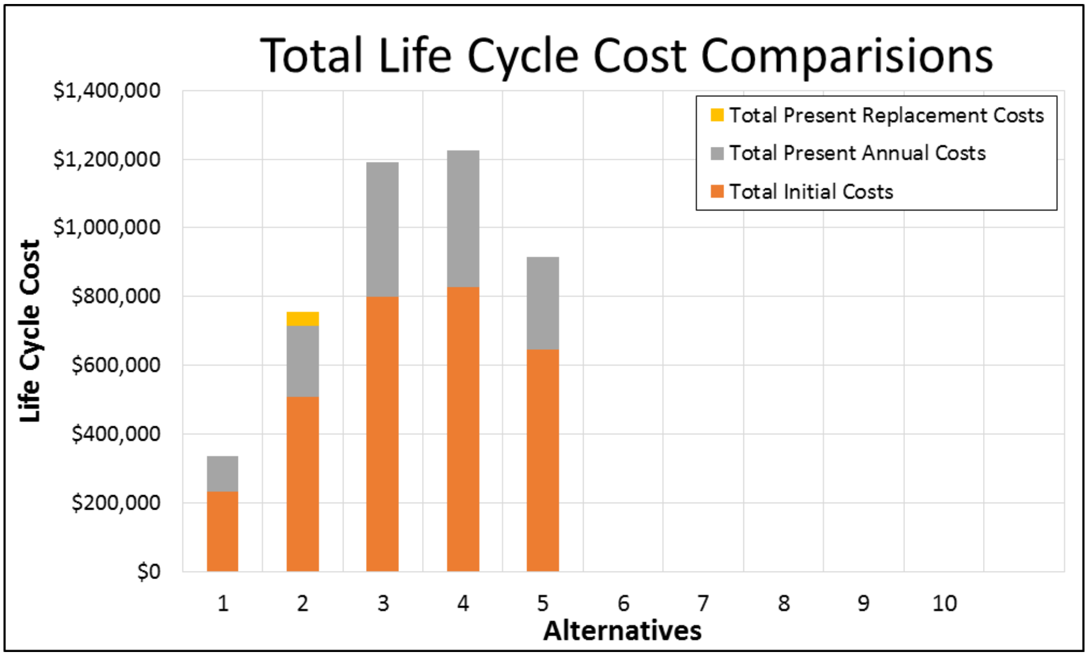


Figure 8.14: LCCAT Total Life Cycle Cost Per Corridor Comparison Bar Graph

8.3.2.2 *User Costs Summary*

In addition to comparisons in raw dollars, calculations were made to allow for comparisons to be made in other metrics. Using cost information presented in the AASHTO Red Book, the difference between scenarios is also presented in values of required user time cost reduction (The higher cost alternative must reduce user time X hrs/day to become the preferred alternative). Using crash value information, differences are also shown in required reductions of crashes.

User Time Cost

Required reduction in user time cost calculations utilize Equation 6 and Equation 7 to develop this value in units of hours/day:

Equation 6: Value of Time per Hour (VT)

$$VT = average\ wage\ \times percent\ of\ wage\ \times vehicle\ occupancy$$

Equation 7: User Time Cost (hour per day over time n)

$$User\ Time\ Cost_T = \frac{\left(\frac{L_i - L_0}{VT_T}\right)}{n \times 365} \times VCP$$

Where:

- L_i = life cycle cost for the i^{th} alternative
- L_0 = lowest life cycle cost for all alternatives in analysis
- VT_T = value of time per hour for transportation mode T
- n = chosen analysis period (years)
- VCP = vehicle classification percentage

The values for user time in hours per day over the analysis time period are calculated first by utilizing recommended values for Equation 6 from the AASHTO Red Book. Shown in Figure 8.15, these values are then used to calculate the user time cost for three modes of transportation: autos, transit, and trucks. To develop a vehicle mix, the mean of 50 records from the ODOT 2014 Summary of Trends was used to determine the default vehicle classification percentage. However, these values are user selectable and can be changed to represent a particular roadway of interest.

Transportation Mode and Trip Purpose	Recommended Percent of Wage / Comp.	Average Wages / Comp.	Average Occupancy	Value of Time per Hour (wage x percentage x occupancy)	Vehicle Classification Percent
Auto Drive Alone / Commute	50%	$18.56	1.50	$13.92	75%
Transit Bus In-Vehicle Commute	50%	$18.56	20.00	$185.60	1%
Truck In-Vehicle Business	100%	$20.23	1.05	$21.24	24%

Figure 8.15: Guidelines for Assigning Values of Time (American Association of State Highway and Transportation Officials 2010)

The resulting graph, shown in Figure 8.16, presents the additional user time benefit that the more expensive alternatives need to provide to be considered as the preferred alternative comprising of the individual vehicle classifications in relation to the lowest cost alternative. This allows for a determination of how much additional user time the higher cost alternative needs to save as a result of better performance, in order for that higher costing alternative to be preferable over the lowest cost alternative. In the example shown, alternative 3 needs to provide a daily time savings of about 15 hours, 12.5 hours for autos and 2.5 hours for trucks, over alternative 1, in order to be considered the preferred alternative.

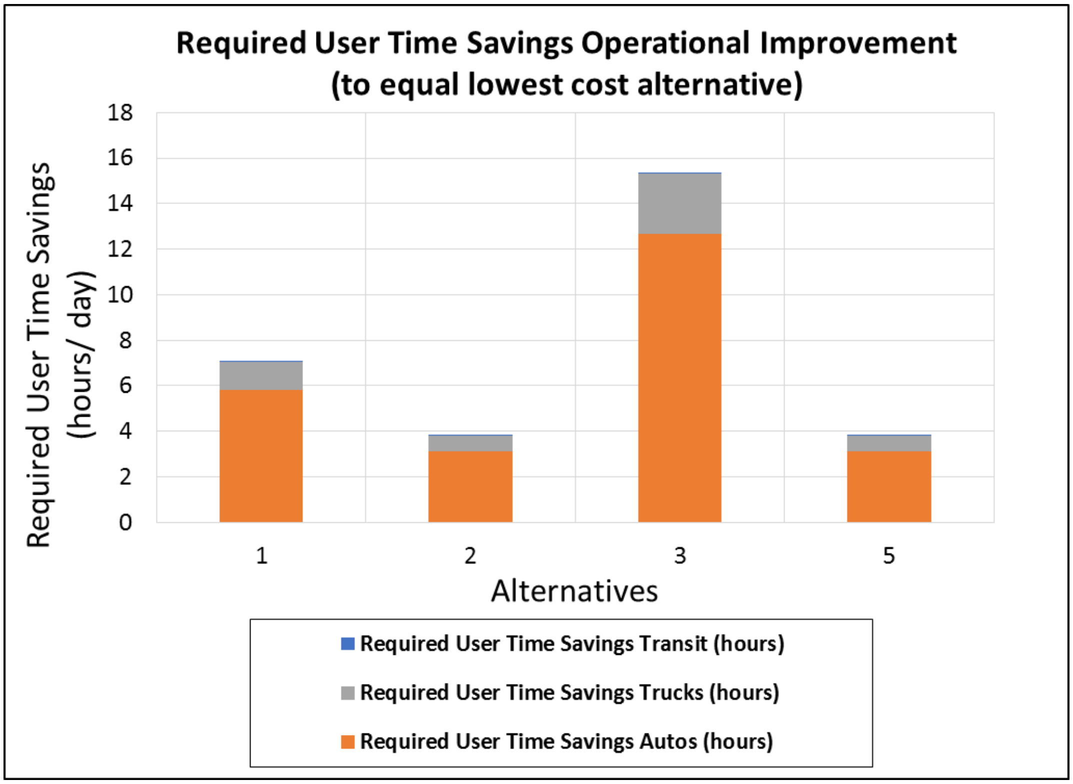


Figure 8.16: LCCAT User Time Saving Requirements Graph

Change in crashes

According to the National Safety Council, the costs of motor-vehicle injuries for 2014 are $1,512,000 for a crash resulting in a fatality and $88,500 for a crash resulting in an incapacitating injury *(National Safety Council 2015)*. These values will be utilized to determine the additional benefits required to justify choosing a more expensive alternative.

8.4 RESULTS AND DISCUSSION

The following results were obtained by utilizing the LCCAT developed for this research. Unless otherwise specified, all analysis comparisons utilize a three percent discount rate, ten-year analysis period, and a ten intersection network (these values are user configurable in the analysis tool). Geometry for each intersection within the analysis network is consistent with that shown in Figure 8.2. Results are presented in a variety of different scenarios.

8.4.1 Vehicle Detection – 1 Intersection | 10 years

This scenario compares the life cycle costs of each type of vehicle detection for one intersection over a ten-year analysis period. This analysis captures the per intersection costs including total initial cost, total present annual cost, and total present replacement cost for each type of vehicle detection. For this analysis each type of detection was installed at stop bar and advance detection locations for both major and minor roads.

Shown in Figure 8.17 inductive loop detection has the lowest life cycle cost for a ten-year analysis period at $20,400 for a single intersection. The alternative with the highest life cycle cost is Wavetronix Radar at $85,469.

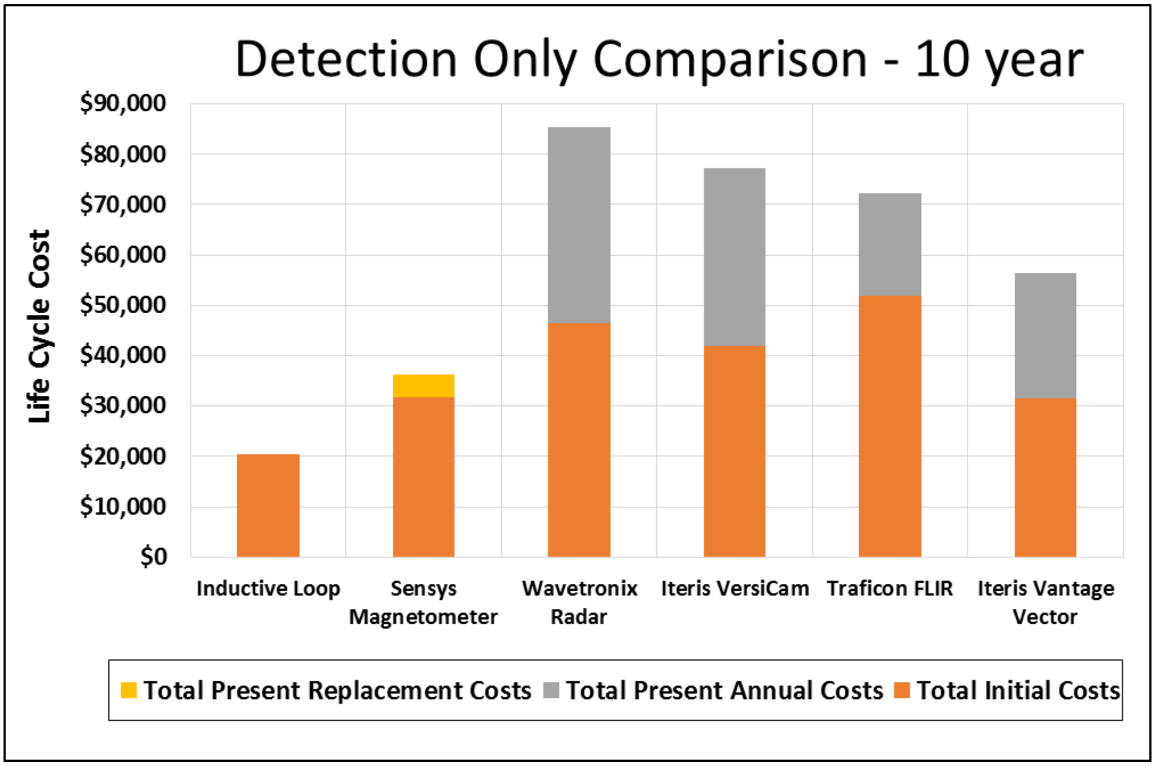


Figure 8.17: Detection only comparisons for 1 intersection over 10 years

Table 8.7: Detection only comparison results for 1 intersection over 10 years

Alternative	Total Initial Costs	Total Present Annual Costs	Total Present Replacement Costs	Life Cycle Cost	Percent Increase in Cost Compared to Lowest
Inductive Loop	$20,400	$0	$0	$20,400	*0.0%*
Sensys Magnetometer	$31,750	$0	$4,629	$33,451	*78.3%*
Wavetronix Radar	$46,520	$38,949	$0	$85,469	*319.0%*
Iteris VersiCam	$42,000	$35,255	$0	$77,255	*278.7%*
Traficon FLIR	$51,984	$20,327	$0	$72,311	*254.5%*
Iteris Vantage Vector	$31,520	$24,880	$0	$56,400	*176.5%*

With the costs developed for this study, the results shown in Table 8.7 reveal that inductive loops not only have the overall lowest life cycle cost and also the lowest initial cost. The overall LCC of the non-invasive products is much higher than the inductive loop, primarily due to the annual maintenance and troubleshooting costs. Of course, this is sensitive to environmental and operation considerations at the deployment sites. If the area is such that loop failures are common, even with new loops, then this analysis would change considerably. In addition, if conditions are dustier, the video camera lens' might require more frequent cleaning than the once/2 years used in this analysis.

Table 8.8 converts the LCCA differences into values of user time and crashes. Non-invasive sensors typically contain additional sets of operational features when compared to inductive loops, and as such, other factors must be taken into consideration. The information presented in Table 8.8 assists with this.

Table 8.8: Detection only user costs results for 1 intersection over 10 years

Alternative	Required User Time Savings (hr / day)		Required Change in Crashes	
	Autos	Trucks	Fatalities	Incapacitating
Inductive Loop	0.00	0.00	0.00	0.00
Sensys Magnetometer	0.24	0.05	0.01	0.18
Wavetronix Radar	0.96	0.20	0.04	0.74
Iteris VersiCam	0.84	0.18	0.04	0.64
Traficon FLIR	0.77	0.16	0.03	0.59
Iteris Vantage Vector	0.53	0.11	0.03	0.41

Radar is the most expensive alternative in this analysis set, however it has the ability to project vehicle arrivals to the stop bar. This ability can provide an increase in efficiency, as better knowledge of vehicle arrivals can assist in the reduction of unintended max-outs, as well as improve the safety of operations, as the exact position of each vehicle within the 'dilemma zone' is known. Video was the second most expensive alternative, but the ability of video to dynamically change the size of the active detection zone can translate into efficiency gains in situations with a large percentage of heavy vehicles within the mix.

The table above shows that required user time savings each alternative must result in to be considered the more preferred alternative. If the deploying agency wishes to utilize radar detection for dilemma zone protection or video for other operational benefits, they would need to see an equivalent decrease of 0.04 crashes resulting in fatalities over the analysis period, or 0.74 decrease in crashes resulting in incapacitating injuries. Similarly, Traficon FLIR thermal detection or Iteris Vantage Vector Hybrid detection can be justified if there is a reduction of 0.03 fatalities over the analysis period in comparison to inductive loops.

8.4.2 Vehicle Detection – 1 Intersection | 5 years

This scenario compares the life cycle costs of each type of vehicle detection for one intersection over a five-year analysis period. This analysis is included in this study as an attempt to capture per intersection costs for each vehicle detection technology with consideration that technologies will not require replacement in a five-year analysis period.

Table 8.8 and Table 8.9 show the results of this analysis, which are similar in scale to that presented for the ten-year analysis period. Figure 8-18 depicts this graphically.

Table 8.9: Detection only results for 1 intersection over 5 years

Alternative	Total Initial Costs	Total Present Annual Costs	Total Present Replacement Costs	Life Cycle Cost	Percent Increase in Cost Compared to Lowest
Inductive Loop	$20,400	$0	$0	**$20,400**	0.0%
Sensys Magnetometer	$31,750	$0	$0	**$31,750**	55.6%
Wavetronix Radar	$46,520	$20,911	$0	**$67,431**	230.5%
Iteris VersiCam	$42,000	$18,928	$0	**$60,928**	198.7%
Traficon FLIR	$51,984	$10,913	$0	**$62,897**	208.3%
Iteris Vantage Vector	$31,520	$13,358	$0	**$44,878**	120.0%

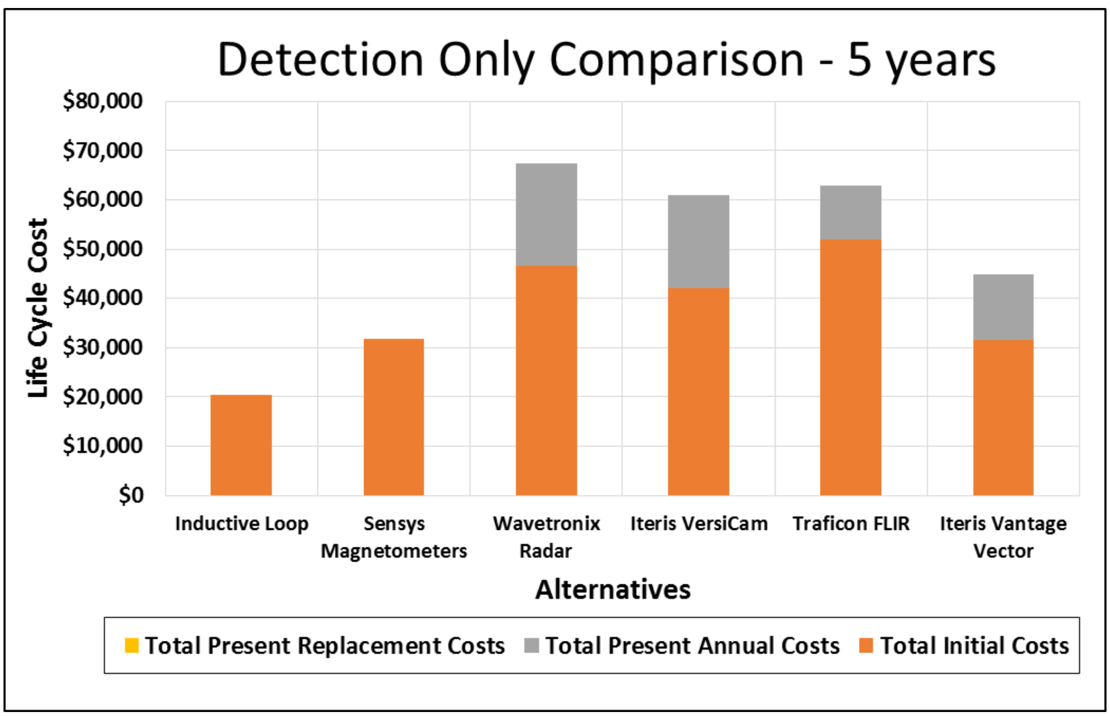


Figure 8.18: Detection only comparisons for 1 intersection over 5 years

Table 8.10 shows the required operational improvements the higher costing alternatives must overcome to be considered the economically preferred alternative.

Table 8.10: Detection only user costs for 1 intersection over 5 years

Alternative	Required User Time Savings (hr / day)		Required Change in Crashes	
	Autos	Trucks	Fatalities	Incapacitating
Inductive Loop	0.00	0.00	0.00	0.00
Sensys Magnetometer	0.34	0.07	0.01	0.13
Wavetronix Radar	1.39	0.29	0.03	0.53
Iteris VersiCam	1.20	0.25	0.03	0.46
Traficon FLIR	1.25	0.26	0.03	0.48
Iteris Vantage Vector	0.72	0.15	0.02	0.28

8.4.3 Vehicle Detection Annual Maintenance Costs

This scenario compares the life cycle costs associated with annual maintenance and troubleshooting cost for each type of vehicle detection. This was included in this study to provide an isolated comparison if an agency is determining the ability to maintain a system long term. Figure 8.19 shows the maintenance cost for each type of detection over a 10 year analysis period.

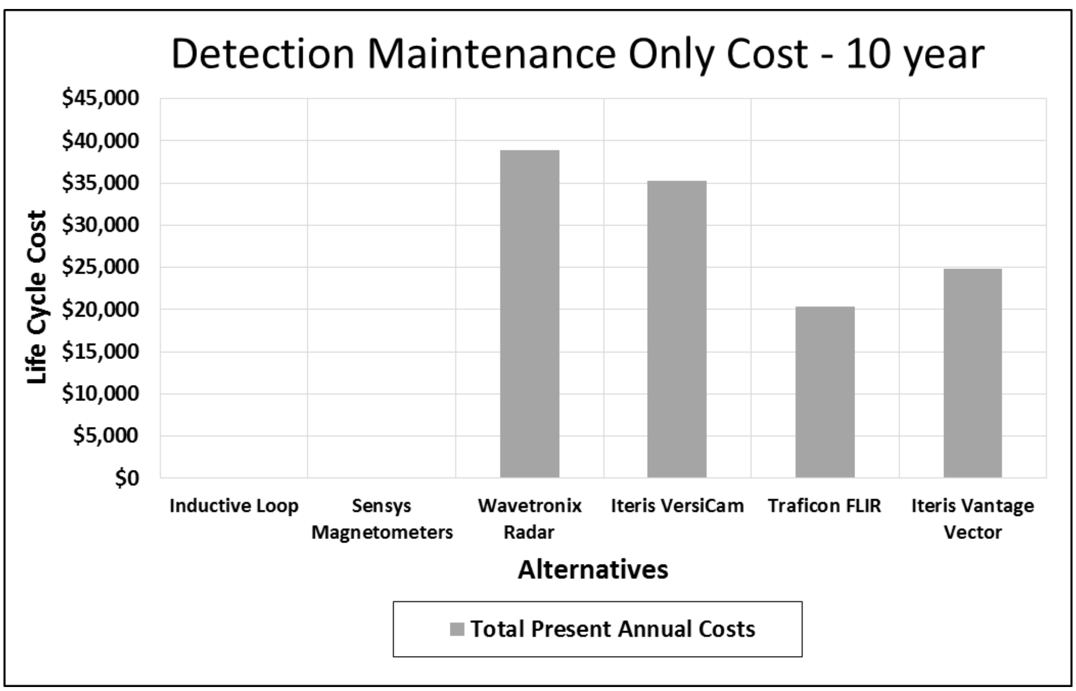


Figure 8.19: Detection maintenance cost for a 10 year life cycle

The figure above shows that Wavetronix Radar units have the most expensive maintenance cost over a 10-year analysis period due to annual troubleshooting and required software upgrades.

8.4.4 Signal Control – 10 Intersections | 10 years

This scenario compares the life cycle costs for each type of signal control technology for ten intersections over a ten-year analysis period. This analysis is included in this study to provide an examination of the isolated life cycle costs for each signal control technology. Additionally, in the event that an ASCT is installed using existing detection, this comparison scenario provides a structured approach to analyzing signal control technologies without the additional costs of vehicle detection.

Shown in Figure 8.20, coordinated signal timing has the lowest life cycle cost for a ten year analysis period. For ten intersections the initial cost for coordinated signal timing is $37,600 for the individual signal timing plans, and the annual cost is $102,362 for retiming every three years. The highest life cycle cost is Transcend at $350,000. The costs that compose each life cycle cost are shown in Table 8.11.

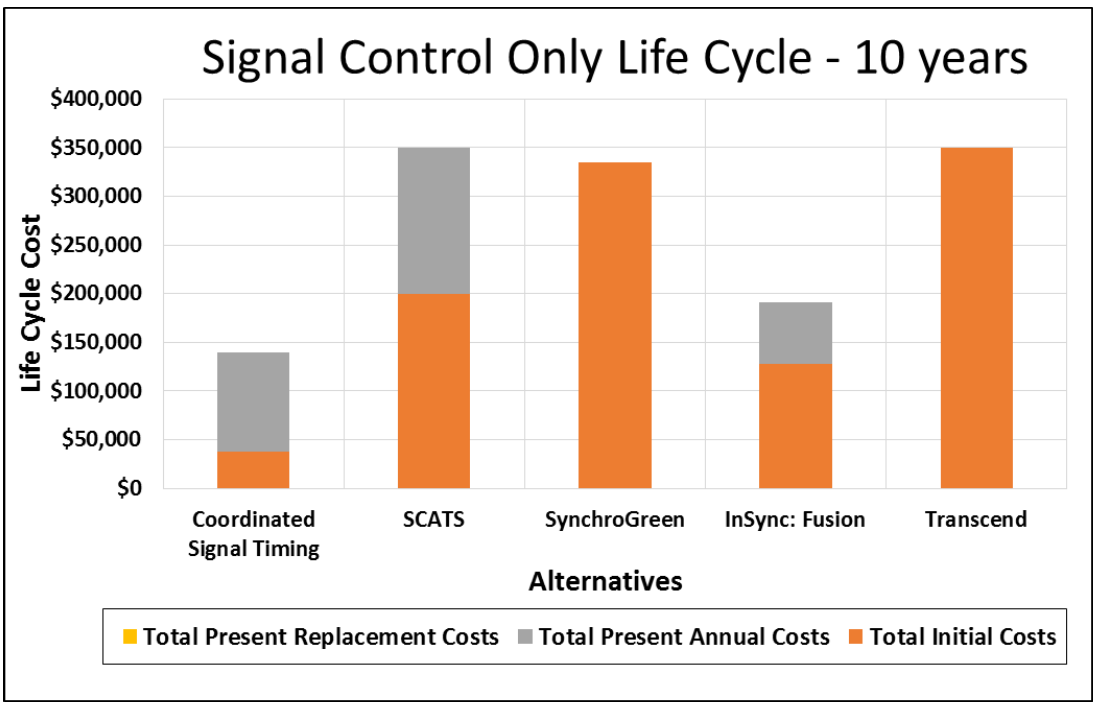


Figure 8.20: Signal control comparisons for 10 year analysis

Table 8.11: Signal control results for 10 year analysis

Alternative	Total Initial Costs	Total Present Annual Costs	Total Present Replacement Costs	Life Cycle Cost	Percent Increase in Cost Compared to Lowest
Coordinated Signal Timing	$37,600	$102,362	$0	**$139,962**	0.0%
SCATS	$200,000	$149,279	$0	**$349,279**	149.6%
SynchroGreen	$335,000	$0	$0	**$335,000**	139.3%
InSync: Fusion	$127,500	$63,977	$0	**$191,477**	36.8%
Transcend	$350,000	$0	$0	**$350,000**	150.1%

This analysis shows over a ten-year period InSync: Fusion adaptive control has slightly higher life cycle cost than the cost of running a roadway network in standard coordination (36.8%). However, SCATS, SynchroGreen, and Transcend will all have a life cycle cost at least double of InSync: Fusion. Consideration should be given to the additional advantage gained from opting to use any of these more expensive alternatives over utilizing basic coordinated signal timing plans that are retimed every three years.

Table 8.12: Signal control user cost results for 10 year analysis

Alternative	Required User Time Savings (hr / day)		Required Change in Crashes	
	Autos	Trucks	Fatalities	Incapacitating
Coordinated Signal Timing	0.00	0.00	0.00	0.00
SCATS	3.09	0.65	0.14	2.37
SynchroGreen	2.88	0.60	0.13	2.20
InSync: Fusion	0.76	0.16	0.03	0.58
Transcend	3.10	0.65	0.14	2.37

8.4.5 Vendor Recommended Detection Installation

Table 8.12 shows the required user time savings and change in crashes the more expensive alternatives must overcome to be considered the preferable alternative. For example, if the deploying agency wishes to install SCATS or Transcend as their ASCT, they expect an equivalent decrease of 0.14 crashes resulting in fatalities over the ten-year analysis period or a 2.37 decrease in crashes resulting in incapacitating injuries compared to coordinated signal timing. Similarly, opting for InSync: Fusion signal control can be justified if there is a reduction of 0.03 fatalities over the analysis period in comparison to coordinated signal timing. Each of the ASCT vendors provide a recommended vehicle detection layout which should be installed by agencies to optimize the adaptive system. In some cases, the ASCT vendors provide specific vehicle detection technologies in addition to which zones are required to operate their system. Therefore, this scenario provides a comparison of the vendor recommended vehicle detection installation. In some cases, such as SynchroGreen and InSync: Fusion, the vendors only specify which detection zones are required, but leave the type of detection up to the agency deploying the system. In such cases, this work uses inductive loops for that detection (The Oregon *2016 Traffic Signal Design Manual* specifies "ODOT's default standard detection type is inductive loops based on their high degree of reliability"*(ODOT Traffic Signal Standards Unit 2016))*. Included in this scenario are the additional/equivalent user costs of the more expensive alternatives in relation to the cheapest alternative. Table 8.13 shows the vendor recommended detection configurations for each type of signal control. Figure 8.21 shows the results of the vendor recommended installation analysis.

Table 8.13: Vendor Recommended Detection Configuration

Signal Control Technology	**Vendor Recommend Detection Configuration**			
	Major Stop bar	**Major Advance**	**Minor Stop bar**	**Minor Advance**
Coordinated Signal Timing	Inductive Loop	Inductive Loop	Inductive Loop	Inductive Loop
SCATS	Inductive Loop	None	Inductive Loop	None
SynchroGreen	Agency Choice*	Agency Choice*	Agency Choice*	Agency Choice*
InSync: Fusion	Agency Choice*	None	Agency Choice*	None
Transcend	Inductive Loop	Agency Choice*	Inductive Loop	Agency Choice*

Agency Choice* = inductive loops for vendor recommended comparison

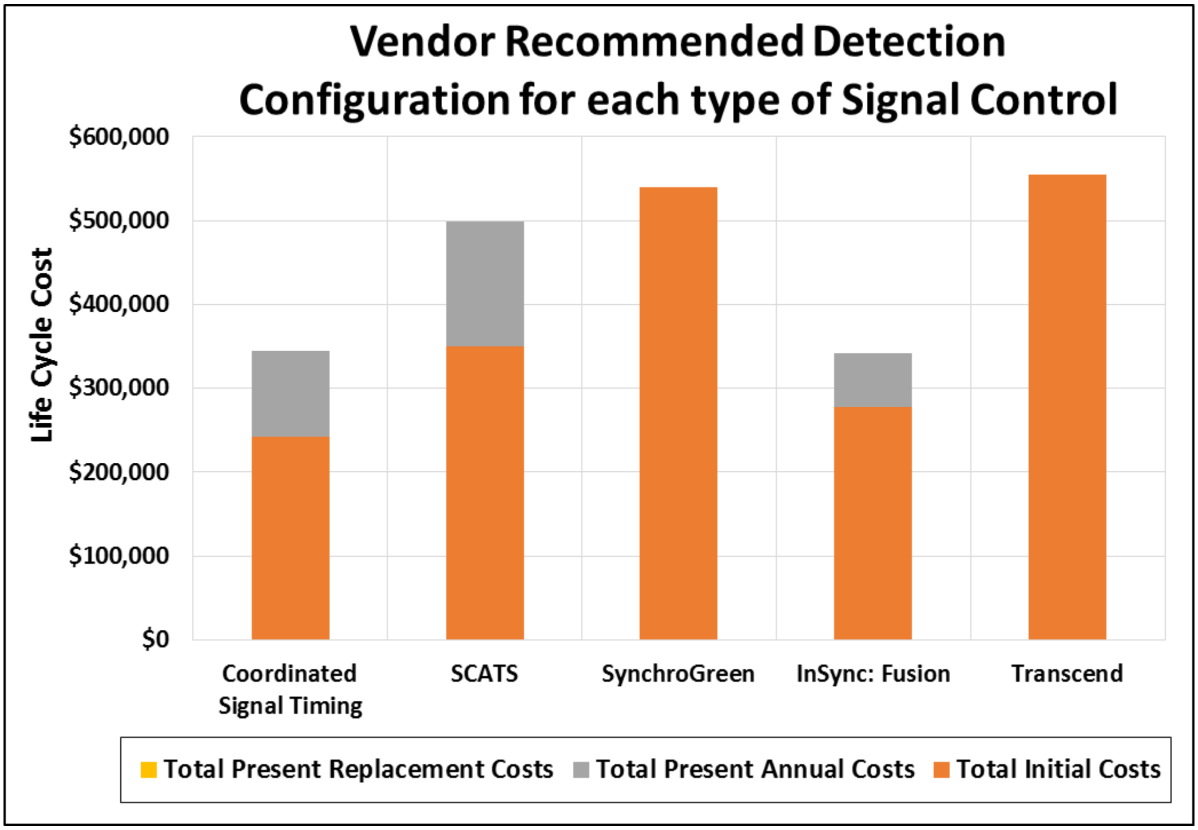


Figure 8.21: Vendor Recommend Installation

Because none of the adaptive systems specify using a technology other than inductive loops, type of detection does not vary in this analysis. In the above figure and summarized in Table 8.14, InSync: Fusion has the lowest life cycle cost of $341,477 consisting of $277,500 in initial costs and $63,977 in annual costs. Coordinated signal timing has the second highest life cycle cost of $343,962 consisting of $241,600 in initial costs and $102,362 in annual costs.

Table 8.14: Vendor recommended detection configuration numeric results

Alternative	Total Initial Costs	Total Present Annual Costs	Total Present Replacement Costs	Life Cycle Cost	Percent Increase in Cost Compared to Lowest
Coordinated Signal Timing	$241,600	$102,362	$0	**$343,962**	0.7%
SCATS	$499,279	$149,279	$0	**$499,279**	46.2%
SynchroGreen	$539,000	$0	$0	**$539,000**	57.8%
InSync: Fusion	$277,500	$63,977	$0	**$341,477**	0.0%
Transcend	$554,000	$0	$0	**$554,000**	62.2%

Table 8.15 summarizes the required user time savings in hours per day and reduction in crashes during the ten year analysis period that the higher cost alternatives must produce in order to be considered the more preferred alternative.

Table 8.15: Vendor recommended detection user cost results

Alternative	Required User Time Savings (hr / day)		Required Change in Crashes	
	Autos	Trucks	Fatalities	Incapacitating
Coordinated Signal Timing	0.04	0.01	0.00	0.03
SCATS	2.33	0.49	0.10	1.78
SynchroGreen	2.92	0.61	0.13	2.23
InSync: Fusion	0.00	0.00	0.00	0.00
Transcend	3.14	0.66	0.14	2.40

8.4.6 Preferred Detection Installation

This comparison scenario presents signal control technologies with preferred vehicle detection technology and placement recommendations from various sources. The SCATS vendor recommended installation calls for only stop bar inductive loop detection, however, an agency may choose to install addition radar advanced detection for dilemma zone protection. These scenarios were determined based on Oregon's *2016 Traffic Signal Design Manual*, ODOT agency survey respondents, and previous research completed by the Georgia Department of Transportation *(Fontaine et al. 2015, ODOT Traffic Signal Standards Unit 2016)*. Summarized in Table 8.16, the preferred coordinated detection configuration calls for major stopbar detection on left turn phase only, and inductive loops for all other zones. For SCATS, it is preferred to use inductive loops to drive the adaptive algorithm and utilize radar detection at advanced location for dilemma zone protection. SynchroGreen has been deployed in several locations which utilizes video detection for stop bar detection and advanced loops for advanced detection *(Fontaine et al. 2015)*. InSync typically comes with proprietary video detection. Therefore, video detection is utilized as the agency preferred detection configuration in combination with radar for advanced detection *(Zhao and Tian 2012)*.

Table 8.16: Preferred Detection Configuration

Signal Control Technology	Preferred Detection Configuration			
	Major Stop bar	Major Advanced	Minor Stop bar	Minor Advanced
Coordinated Signal Timing	Inductive Loop Left Turn Only	Inductive Loop	Inductive Loop	Inductive Loop
SCATS	Inductive Loop	Radar	Inductive Loop	Radar
SynchroGreen	Video	Inductive Loop	Video	Inductive Loop
InSync: Fusion	Video	Radar	Video	Radar
Transcend	Inductive Loop	Radar	Inductive Loop	Radar

Finally, Transcend typically utilizes existing inductive loop technology, and radar detection is installed to monitor advanced detection. Included in this scenario are the additional/equivalent user costs of the more expensive alternatives in relation to the cheapest alternative. Figure 8.22 and Table 8.17 show the results of the vendor recommended installation analysis.

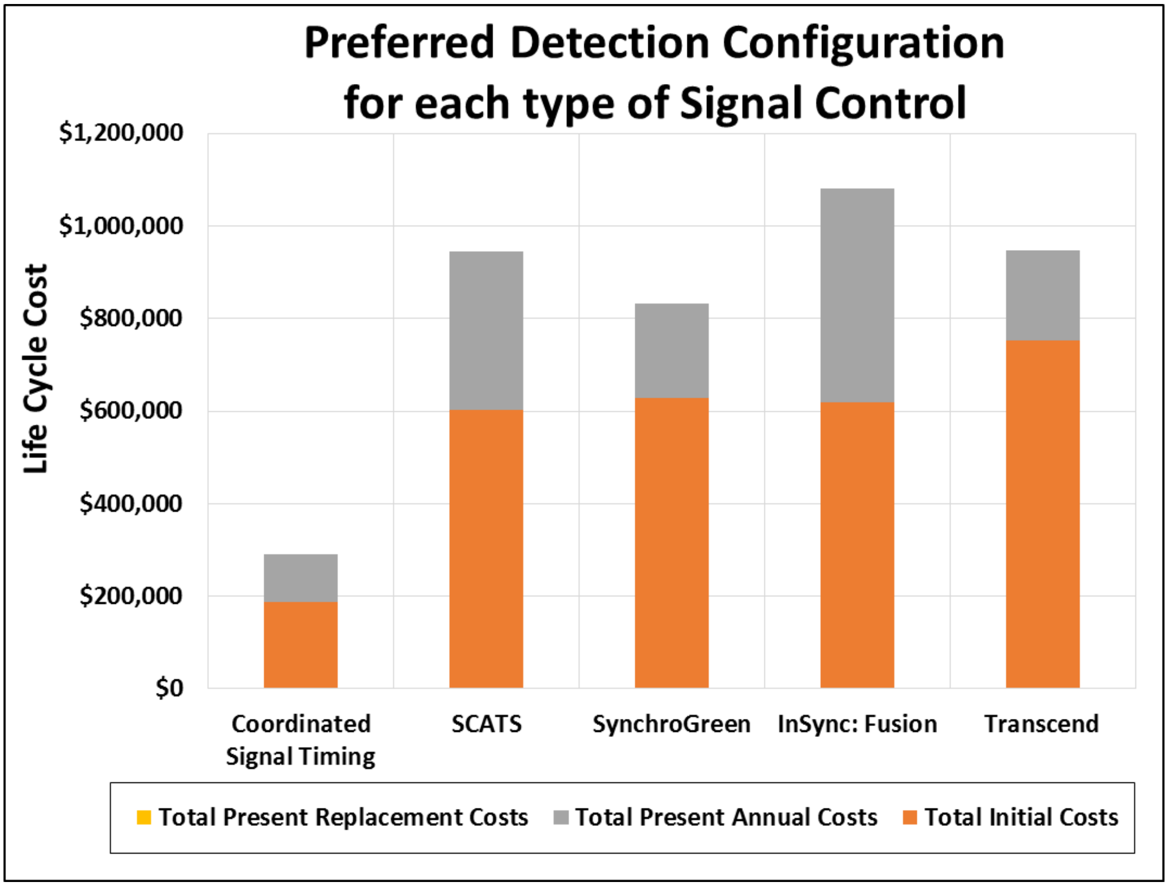


Figure 8.22: Preferred installation 10 year analysis

Coordinated signal timing has the lowest life cycle cost of $289,962 consisting of $187,600 in initial costs and $102,362 in annual costs. This life cycle cost is 14% less than the vendor recommended coordinated signal timing as there are eight less inductive loops per major approach. InSync: Fusion has the highest life cycle cost of $1,081,096 consisting of $619,100 in initial costs and $461,996 in annual costs. This life cycle cost is 272.8% higher than vendor recommended coordinated signal timing cost as a result of utilizing video detection for stop bar and radar detection for dilemma zone. The required changes in user benefits are shown in Table 8.18.

Table 8.17: Preferred installation 10 year analysis numeric analysis

Alternative	Total Initial Costs	Total Present Annual Costs	Total Present Replacement Costs	Life Cycle Cost	Percent Increase in Cost Compared to Lowest
Coordinated Signal Timing	$187,600	$102,362	$0	**$289,962**	0.0%
SCATS	$601,600	$344,023	$0	**$945,623**	226.1%
SynchroGreen	$629,000	$203,275	$0	**$832,275**	187.0%
InSync: Fusion	$619,100	$461,996	$0	**$1,081,096**	272.8%
Transcend	$751,600	$194,745	$0	**$937,345**	226.4%

Table 8.18: Preferred detection configuration user costs 10 year analysis

Alternative	Required User Time Savings (hr / day)		Required Change in Crashes	
	Autos	Trucks	Fatalities	Incapacitating
Coordinated Signal Timing	0.00	0.00	0.00	0.00
SCATS	9.68	2.03	0.43	7.41
SynchroGreen	8.05	1.69	0.36	6.13
InSync: Fusion	11.72	2.46	0.52	8.94
Transcend	9.60	2.01	0.43	7.42

Of note with this analysis is the large change in overall system (detection + control) life cycle costs with changes in detection. For example, by switching detection from inductive loops to video cameras for InSync: Fusion, the system went from having the lowest life cycle cost to the highest, illustrating that the agency choice of detection impacts not only the accuracy and precision of the driven system, but also the bottom line over the lifetime of the installation.

8.4.7 Inductive Loop Sensitivity Analysis Results

This comparison scenario provides the additional cost associated with a shortened life span of inductive loops detectors. Inductive loops consistently produced the lowest life cycle cost throughout this analysis due to a lower initial installation cost compounded by the lack of annual maintenance and troubleshooting. However, it is noted that inductive loops may not last as long as expected due to construction, pavement failure, freeze thaw cycles, or vermin. Figure 8.23 shows the loop life span sensitivity analysis for ten intersections over ten years. The sensitivity analysis reveals that as the lifespan of a loop detector is shortened, the life cycle cost increases exponentially. Decreasing the life span from ten years to six years results in an increase in life cycle cost of 50% and decreasing the life span from five years to one year results in an increase in life cycle cost of 596%. Therefore, careful consideration should be made for networks that desire to utilize inductive loops as their source of vehicle detection, but may encounter shorter loop detector lifespans as a result of repeated construction, extreme freeze thaws, or other factors mentioned previously.

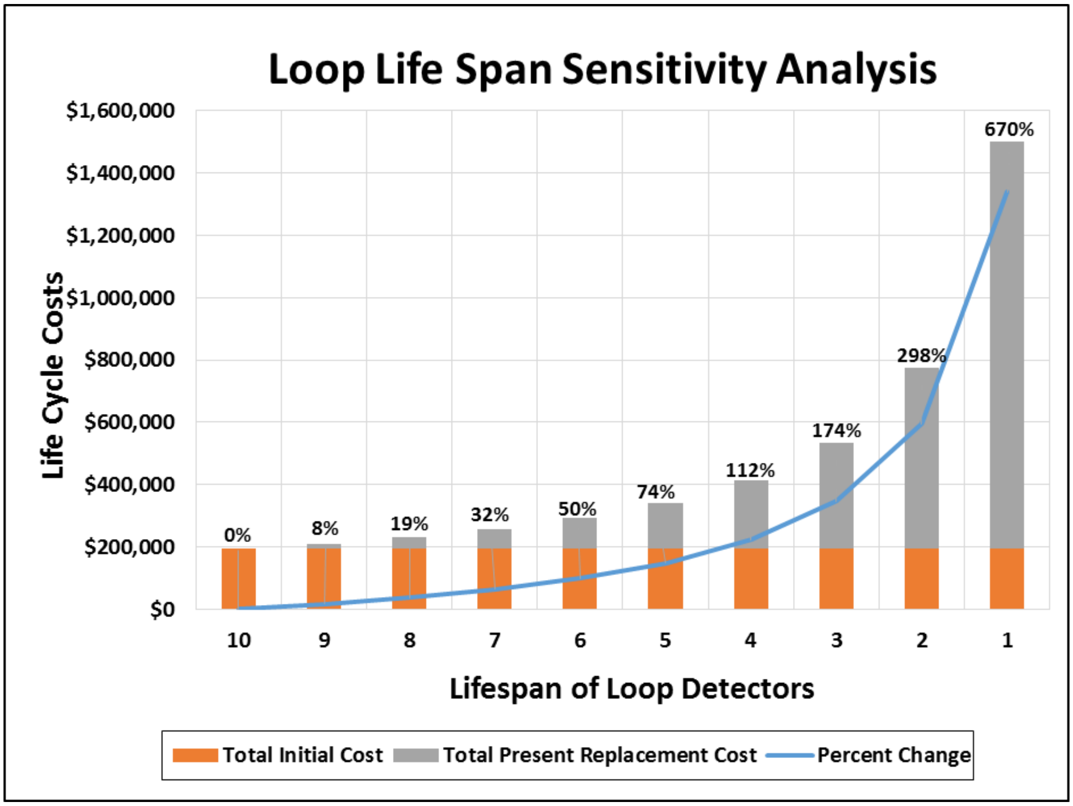


Figure 8.23: Loop life span sensitivity analysis

8.5 RESULTS AND DISCUSSION SUMMARY

This section has provided results and discussions for technology specific life cycle cost comparisons of vehicle detection and signal control individually, detection maintenance costs, and vendor recommended and preferred detection installations, as well as an inductive loop lifespan sensitivity analysis. Additional / equivalent user costs were presented to provide baseline measurements to determine if an alternative with a higher life cycle cost could be justified due to an increase in performance (efficiency or safety). Inductive loops consistently were the lowest cost alternative, due to low initial cost and no maintenance while the non-invasive technologies had higher initial costs as well as required maintenance, cleaning, software, and troubleshooting visits that drove up the life cycle cost of those units. The important points of this analysis are the following:

- Choice of detection has a great impact on overall life cycle cost of an adaptive control system

- InSync: Fusion was shown to have a lower life cycle cost than coordinated operation with vendor recommended detection

- Life cycle cost of any system using inductive loops is extremely sensitive to the expected lifespan of the installed loops

- Annual maintenance, including cleaning and troubleshooting, contribute to non-invasive detection having much higher life cycle costs than inductive or magnetic sources.

- Sensys pucks are the only detection source used in this analysis that required replacement within the ten-year lifespan used in this work

- While non-invasive detection devices have higher initial and life cycle costs than inductive loops, these costs can be offset by relatively modest improvements in safety and efficiency that may be available due to advanced feature sets of the non-invasive units when compared to inductive loops

9.0 RECOMMENDATIONS AND CONCLUSIONS

In this work, event based data was collected from advance and stop bar detectors at four different sites across Oregon with inductive loop detection co-located with various non-invasive detection technologies. Qualitative and quantitative analysis techniques were used including quantile regression, linear regression, and multinomial logit models to develop recommendations for deployment of non-invasive detection devices. Metrics analyzed for this work were selected because of their applicability to most adaptive algorithms common to the marketplace, and included:

- Advance Detection (detection located 100 for or more from the stop bar)
    - Activations in a 5-minute bin
    - Occupancy in a 5-minute bin
    - Time to gap out
- Stop bar Detection (detection located at or within 100 feet of stop bar)
    - Time to gap out
    - Time to first sustained call on red
    - Split failure identification (Green and Red Occupancies)

Following the analysis of these metrics, a Life Cycle Cost analysis was performed investigating the overall cost of detection and adaptive control over various analysis periods. Recommendations and conclusions from this work are as follows.

9.1 RECOMMENDATIONS

Over 1900 hours of data was collected across 40 different sensor couples at the four sites, however after inductive loop ground truthing and data cleansing, sixteen sensor couples remained for analysis. Recommendations from this work are the following:

9.1.1 Advance Detection

Data collected for analysis focused on a scenario when the non-invasive detector was mounted on the mast arm / luminaire on the far side of the intersection (with the exception of the radar at 97th).

9.1.1.1 Activations

Activation differences under the observed conditions had an error range of (-10 to 2) activations per 5-minute period, but based upon the actual range of activations for the 5-minute bins (20 to 60), errors were observed to be as high as 50% in some cases. Site specific conditions tend to impact the difference range significantly. Based upon this work, it is not recommended to develop advance vehicle counts / activations with a stop bar mounted video sensor at this time. Radar sensors were available at two locations, however the performance compared with the other sensors was inconsistent. Given that there were only two radar zones, more work is needed to investigate the radar sensors prior to making a recommendation for activations with this sensor.

9.1.1.2 Occupancy

Discrepancies between loop and video varied greatly from site to site, with some discrepancies as high as 0.5 while others were relatively minor. Quantile regression modeling noted performance is better towards the ends of the operation spectrum (occupancies close to 0.0 and 1.0) with more discrepancies during medium to heavy traffic conditions. There were many differences that occurred between the sites, including mounting height, traffic volume, and video sensing technology, but these could not be quantified with the data set. As such, it is not recommended to generate occupancy in an advanced detection zone with a stop bar mounted video sensor. There were limited zones with radar detection analyzed, but based upon this work; radar is promising for developing occupancy at an advanced zone.

9.1.1.3 Time to Gap

For TTG, only 68% of the time did video and loop detect a gap at about the same time, and this did vary significantly between intersections. A variety of other factors impacted this value, including mounting height, traffic volumes, and sensor technology, but based upon this work, radar looks promising for determining gaps in an advanced detection zone but video would not, when mounted at the stop bar.

9.1.2 Stop Bar Detection

For stop bar analysis, the trends noted were consistent with those identified in the advance detector analysis. Specific recommendations follow.

9.1.2.1 Time to Gap and Time to First Sustained Call

Generally, TTG and TFSC had reasonable performance with several sensor pairs observed with similar performance 90% of the time though there were sensor pairs which experienced normal data only 75%-80% of the time. For TTG, performance was reasonably consistent during very low volume as well as very high volume periods while for TFSC, the video sensor was more consistent with the loop output when traffic volumes are higher. It would be reasonable to deploy video for stop bar detection with the knowledge that modest differences will occur under certain operational regimes.

9.1.2.2 Split Failure Identification (Green and Red Occupancy)

A combination of occupancy on green and during the last 5 seconds of red can be used to identify split failures. Analysis of data used to drive this identification showed GORs of loop sensors and video sensors generally showed some linear trends, but the ROR_5s of loop sensors and video sensors were completely unmatched (upper left and upper right). Because of this, it is not recommended to use any occupancy based metric from a stop bar video sensor.

9.1.3 Life Cycle Cost Analysis

Comparisons made within the life cycle cost analysis included those between vehicle detection and signal control individually, detection maintenance costs, and vendor recommended and preferred detection installations, as well as an inductive loop lifespan sensitivity analysis. Inductive loops consistently were the lowest cost alternative, due to low initial cost and no maintenance while the non-invasive technologies had higher initial costs as well as required maintenance, cleaning, software, and troubleshooting visits that drove up the life cycle cost of those units. Also, choice of detection has a great impact on overall life cycle cost of an adaptive control system with the life cycle cost of any system using inductive loops is extremely sensitive to the expected lifespan of the installed loops. Lastly, while non-invasive detection devices have higher initial and life cycle costs than inductive loops, these costs can be offset by relatively modest improvements in safety and efficiency that may be available due to advanced feature sets of the non-invasive units when compared to inductive loops. Therefore, while the accuracy and precision is of great importance when selecting a detection technology, the life cycle cost of the various detection technologies, advanced feature sets of the units, and the abilities for field crews to troubleshoot and maintain these systems, should all be taken into consideration when specifying a detection unit.

9.2 CONCLUSIONS AND FUTURE WORK

A number of recommendations for selection and deployment of non-invasive detection technologies have been made in this document; however one item that was learned during the course of this work is that it is incredibly important to conduct routine, preferably continuous, detector health monitoring to ensure that whatever type of detection deployed is operating properly. While a call and extend stop bar sensor that is not functioning properly will certainly cause operational issues, these issues will be limited to the current cycle, although problems on consecutive phases can compound each other. Any detection zone, be it loop, radar, or video, that provides inconsistent data used to drive an adaptive algorithm can result in the adaptive system operating in a constant state of flux. As such, detector health is extremely important. This can be conducted through co-located sensors, close monitoring of sensor outputs, or other means, but regardless, it needs to be part of a deployment plan for an adaptive system. It should be noted more than half the loops that were studied in this research produced missed/false calls greater than 10% during a randomly selected manual ground truth period. This technology is considered to be the most reliable and accurate technology by the industry.

At the onset of this work, it was believed that mathematical correction factors could be developed and applied to non-invasive sensors being used in place of an invasive device;

however it is apparent that there are many site and technology specific characteristics that can impact the outputs of these devices greatly. As such, an operator must take the recommendations provided herein and apply them to each individual situation. There is no broad brushed recommendation that can be made for deployment of detection technology; an engineer's judgement and analysis of the tools available from each device, its general performance, as well as initial and long term costs must be considered when making this decision. Future work in this area can be performed in several areas. First, to directly continue this work, one would continue to collect additional data sets at locations with co-located sensors to provide a more robust data set from wherein the factors identified in this work that contributed to differing performance between detection couples could be quantified. Ideally, experiments would be designed expressly to isolate the various factors discussed, data collected, and models built to focus on specific items. Second, on a broader note, a long term before / after could be commissioned to investigate the monetary benefits of the advanced feature sets in non-invasive detection devices. While vendors, practitioners, and to some degree researchers continue to speak highly about the ability to track vehicles through a detection zone, change detection zone size by phase color, and other features, the monetary benefits of these features have yet to be quantified in a real world environment.

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