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PERFORMANCE EVALUATION OF TRAFFIC SENSING AND CONTROL DEVICES

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16. Abstract

High quality vehicle detection is essential to properly operate actuated phases at traffic signals and to facilitate effective management of technician and engineering resources. INDOT operates over 2600 traffic signal controllers, approximately 2000 of which use some form of vehicle detection. The private sector continues to develop innovative sensing technologies that may potentially benefit Indiana motorists and taxpayers by improving system efficiency and lowering installation and maintenance costs. However, the acceptance of new sensing technology requires careful evaluation because to ensure that they provide robust performance 24 hours a day, 365 days a year, with minimal impact on maintenance resources.

This study developed a technical protocol for evaluating vehicle detector performance and applied those techniques to both video detection (in partnership with Texas) and wireless magnetometers. Based on experiences in designing the detector test bed, recommendations are given for stop bar detection zone design using wireless magnetometers. Additional results include a detailed study of the inductive loop detector sensing range for several loop geometries, and an innovative method for interrogating NTCIP-compliant traffic signal systems to allow quality control on signal timing plan implementation. Since this project spanned several years, interim results were documented in the professional literature as they became available. This technical report summarizes those results and provides references to the published papers.

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EXECUTIVE SUMMARY

PERFORMANCE EVALUATION OF TRAFFIC SENSING AND CONTROL DEVICES

Introduction

High quality sensing and control systems are essential for providing efficient signalized arterial operations. INDOT operates over 2600 traffic signal controllers, approximately 2000 of which use some form of vehicle detection. The private sector continues to develop innovative sensing technologies that may potentially benefit Indiana motorists and taxpayers by improving system efficiency and lowering installation and maintenance costs. However, the acceptance of new sensing technology requires careful evaluation because to ensure that they provide robust performance 24 hours a day, 365 days a year, with minimal impact on maintenance resources.

This project was initiated with the objective of assisting INDOT with evaluating new sensing and control technology. As the project progressed, there were several opportunities to partner with colleagues at other agencies, institutions, and businesses to leverage collective resources and accelerate implementation on a national scale.

Findings

This study developed a technical protocol for evaluating vehicle detector performance and applied those techniques to both video detection (in partnership with Texas) and wireless magnetometers. Based on experiences in designing the detector test bed, recommendations are given for stop bar detection zone design using wireless magnetometers. Additional results include a detailed study of the inductive loop detector sensing range for several loop geometries, and an innovative method for interrogating NTCIP-compliant traffic signal systems to allow quality control on signal timing plan implementation. Since this project spanned several years, interim results were documented in the professional literature as they became available. This technical report summarizes those results and provides references to the published papers.

A methodology for evaluating vehicle detectors was developed in a collaborative effort with Texas Transportation Institute in an effort to broaden national support for better performing vehicle detector specifications such as those adopted by INDOT. This research effort helped define how detection technology should be evaluated (and promoted developing a national consensus).

This testing methodology was directly applied to evaluation of wireless magnetometers. The evaluation concluded found that these detectors met the standards of ITM 934, with the stipulation that detection zone designs must be carefully designed. During this project several lessons were learned regarding the detection zone configuration during an iterative design and testing process carried out between the research team and staff from Sensys. Recommendations for detector spacing were developed as a result of this process.

Additional research included an investigation into the sensitivity of loop detectors of different geometries. Although loop detectors have been in use since the 1920s, there has been practically no published research documenting the comparative sensitivity of alternative loop designs with empirical data. We have carried out a study under controlled conditions for four common loop designs that measured the response of the loops to a simulated vehicle undercarriage at different vertical and horizontal locations relative to the loop. We observed no differences among the four geometries regarding the spread of the detection area into adjacent lanes. It was also found that a certain loop geometry that was expected to have enhanced sensitivity in the loop center actually exhibited less sensitivity over that region.

Finally, another topic that the research team was asked to investigate was the possibility of developing a methodology for checking traffic signal controller settings for consistency across intersections. The research team worked with an industry partner to develop a tool that would populate a database table with the signal controller settings by investigating all of the nodes of the NTCIP tree by executing a walk of the tree using the standard SNMP protocol.

Implementation Recommendations

The results of this project have had a positive impact on agency operations prior to the release of the final report. INDOT has currently adopted the vehicle detector evaluation methodology as ITM No., 934-08P. The evaluation of wireless magnetometers led to the addition of this new detector technology to the approved materials list, which will potentially reduce detector installation and maintenance costs, as well as potentially allow enhanced information to be collected from signal systems. The magnetometers have been used to actuate the traffic signal at the SPR-3206 test intersection since 2009, and may open the way for the development of an improved vehicle detection standard and lead to more effective methods of constructing new signalized intersections.

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CHAPTER 1. OVERVIEW OF RESEARCH RESULTS

1.1. Introduction

This is the final report for JTRP project SPR-3206, "Performance Evaluation of Traffic Sensing and Control Devices." This project began in January 2008 and concluded in October 2011. The project benefited from extensive in-kind vendor support. In addition, the Texas Transportation Institute provided funds that provided an opportunity to collaborate with colleagues in Texas to develop consensus on methods for assessing vehicle detection technology accuracy and develop consensus on target performance thresholds.

To facilitate early dissemination of the research findings, several intermediate technical papers were prepared and published or submitted to peer-reviewed journals:

1. Middleton, D., R. Longmire, D.M. Bullock, and J.R. Sturdevant, "A Proposed Specification Concept for Vehicle Detection." In *Transportation Research Record No. 2128*, TRB, National Research Council, Washington, DC, pp.161–171, 2009.
2. Day, C.M., Premachandra, H., Brennan, T.M., Sturdevant, J.R., and Bullock, D.M. "Operational Evaluation of Wireless Magnetometer Vehicle Detectors at a Signalized Intersection." In *Transportation Research Record No. 2192*, Transportation Research Board of the National Academies, Washington, DC, pp. 11–23, 2010.
3. Day, C.M., Brennan, T.M., Harding, M.L., Premachandra, H., Jacobs, A., Bullock, D.M., Krogmeier, J.V., and Sturdevant J.R. "Three Dimensional Mapping of Inductive Loop Sensitivity with Field Measurement." In *Transportation Research Record No. 2128,* Transportation Research Board of the National Academies, Washington, D.C., pp. 35–47, 2009.
4. Technical paper on use of NTCIP communication protocol for implementing quality control and consistency checks of corridor traffic signal controller parameter configuration. At time of report submission, this paper was in production stage and scheduled to be completed by the TRB July 31, 2011 deadline. This paper will be distributed to the SAC in early August.

This report is structured as an executive summary in which the major findings of the above papers are outlined. The reader is referred to the above documents for additional details of the work. Further information on each paper is provided in Appendix A.

1.2. Objective

This objective of this project is to build upon past efforts by INDOT to improve the state of the practice for testing and operating traffic sensing and control devices. High quality traffic signal detection is essential to properly operate actuated signal phases and collect high quality traffic data to facilitate effective management of technician and engineering resources (1,2,3,4,5,6,7,8,9,10,11,12,13). INDOT operates over 2600 traffic signal controllers, approximately 2000 of which use some form of vehicle detection. New innovations from the private sector offer potential cost savings from the promise of cheaper installation and reduced maintenance cost. However, these cost savings must be balanced with an evaluation of the detector performance to ensure that the technology performs as well as existing detectors, but also to ensure that the control devices deliver the promised performance.

Vehicle detection at traffic signals is a detector application where little tolerance for failure is acceptable. For actuated phase operation, failure to detect a vehicle waiting to receive the right-of-way can lead to excessive delay or encourage the waiting motorist to make unsafe maneuvers. Excessive numbers of false detections leads to the less severe but nonetheless unacceptable scenario where time is wasted serving green time to movements when no demand is present while other movements have vehicles waiting. Past experiences by INDOT have suggested that extensive testing in the freeway domain is not directly applicable to stop bar presence detection. We have proposed a new methodology for evaluating detectors that is applicable to the domain of intersection operations. This methodology was developed in partnership with the Texas Transportation Institute. We have directly applied that methodology in the evaluation of wireless magnetometers. These findings are described in Chapter 2 and Chapter 3.

Two additional research efforts were carried out during SPR 3206. The impact of loop detector geometry on the sensitivity of detection zones to the presences of vehicles with varying vertical clearance was measured in the field with a test apparatus simulating the presence of a vehicle undercarriage under precise conditions. That research helped substantiate practitioner experience with empirical data. Another important aspect of operations that is coupled with detector evaluation is the programming of actuated traffic signal controllers. With literally tens of thousands of changeable parameters, there are numerous opportunities for errors to accumulate during the programming process. This report describes a methodology for checking the consistency of traffic signal settings with an essentially automated process. These findings are described in Chapter 4 and Chapter 5.

1.3. Summary of Principle Findings

A methodology for evaluating vehicle detectors was developed in a collaborative effort with Texas (Dan Middleton and Ryan Longmire) in an effort to broaden national support for the ITM 934[1] drafted by INDOT in 2008. The methodology is summarized in Chapter 2, and a reprint of the paper is included for project reviewers in Appendix A. This paper is important for defining (and developing national consensus) on how detection technology should be evaluated. The paper is structured such that there is close agreement on the assessment techniques, but somewhat diverging agreement on the thresholds for success. To address those

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[1] http://www.in.gov/indot/div/M&T/itm/pubs/934_testing.pdf

diverging views, the paper contains both the values obtained from video detection as well as those proposed by INDOT.

This testing methodology was directly applied to evaluation of wireless magnetometers. This evaluation was carried out as a collaborative effort with the manufacturer (Sensys Networks, Inc). The evaluation concluded found that these detectors met the standards of ITM 934, with the stipulation that detection zone designs must be carefully designed. Naturally, this is true of any detector type. However, during this project several lessons were learned regarding the detection zone configuration during an iterative design and testing process carried out between the research team and staff from Sensys. Recommendations for detector spacing were developed as a result of this process. The results are summarized in Chapter 3, and a reprint of the paper is included for project reviewers in Appendix B.

TABLE 1.1
Comparison of 10-year lifetime cost of detection at an intersection of two 2-lane roads with both advance detection on all approaches, and stop bar detection on eight lanes at the intersection. Note: these costs are estimated by local distributor for Sensys Networks, Inc.

Installation Cost	$57,757	$89,000
Maintenance Cost (10 Year)	$3,650	$2,000
Replacement Cost (10 Year)	$720	$10,920
Total cost of Ownership (10 Years)	$62,127	$101,920

Additional research carried out under SPR 3206 included an investigation into the sensitivity of loop detectors of different geometries. Although loop detectors have been in use since the 1920s, there has been practically no published research documenting the comparative sensitivity of alternative loop designs with empirical data. We have carried out a study under controlled conditions for four common loop designs that measured the response of the loops to a simulated vehicle undercarriage at different vertical and horizontal locations relative to the loop. We observed no differences among the four geometries regarding the spread of the detection area into adjacent lanes. It was also found that a certain loop geometry that was expected to have enhanced sensitivity in the loop center actually exhibited less sensitivity over that region. Additional details are provided in Chapter 4, and a reprint of the paper is included for project reviewers in Appendix C.

Finally, another topic that the research team was asked to investigate was the possibility of developing a

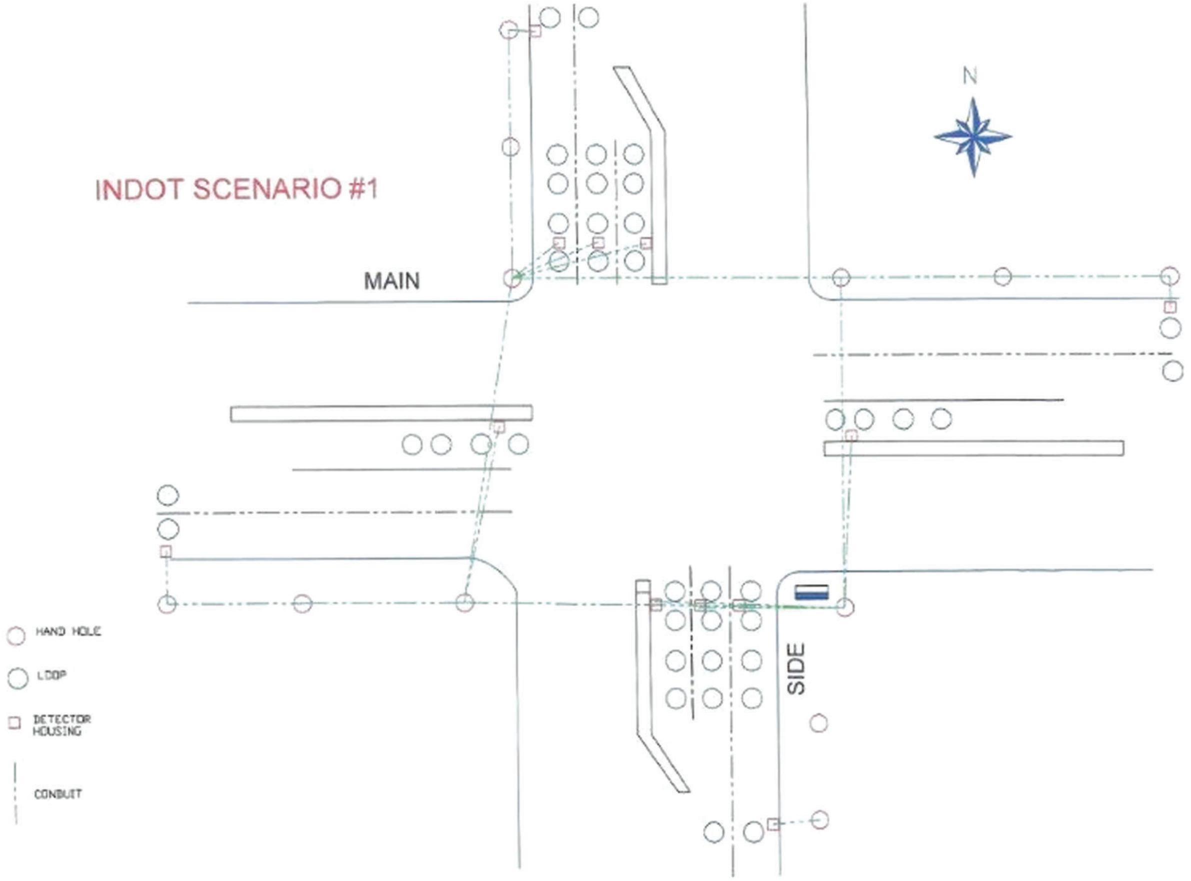


Figure 1.1 Detector configuration used to estimate costs in Table 1.1

methodology for checking traffic signal controller settings for consistency across intersections. The research team worked in partnership with developers at Econolite Control Products to develop a tool that would populate a database table with the signal controller settings by investigating all of the nodes of the NTCIP tree by executing a walk of the tree using the standard SNMP protocol. Results from this study are provided in Chapter 5.

1.4. Estimated Benefits

Table 1.1 shows a comparison of 10-year lifetime costs for wireless magnetometers versus inductive loops

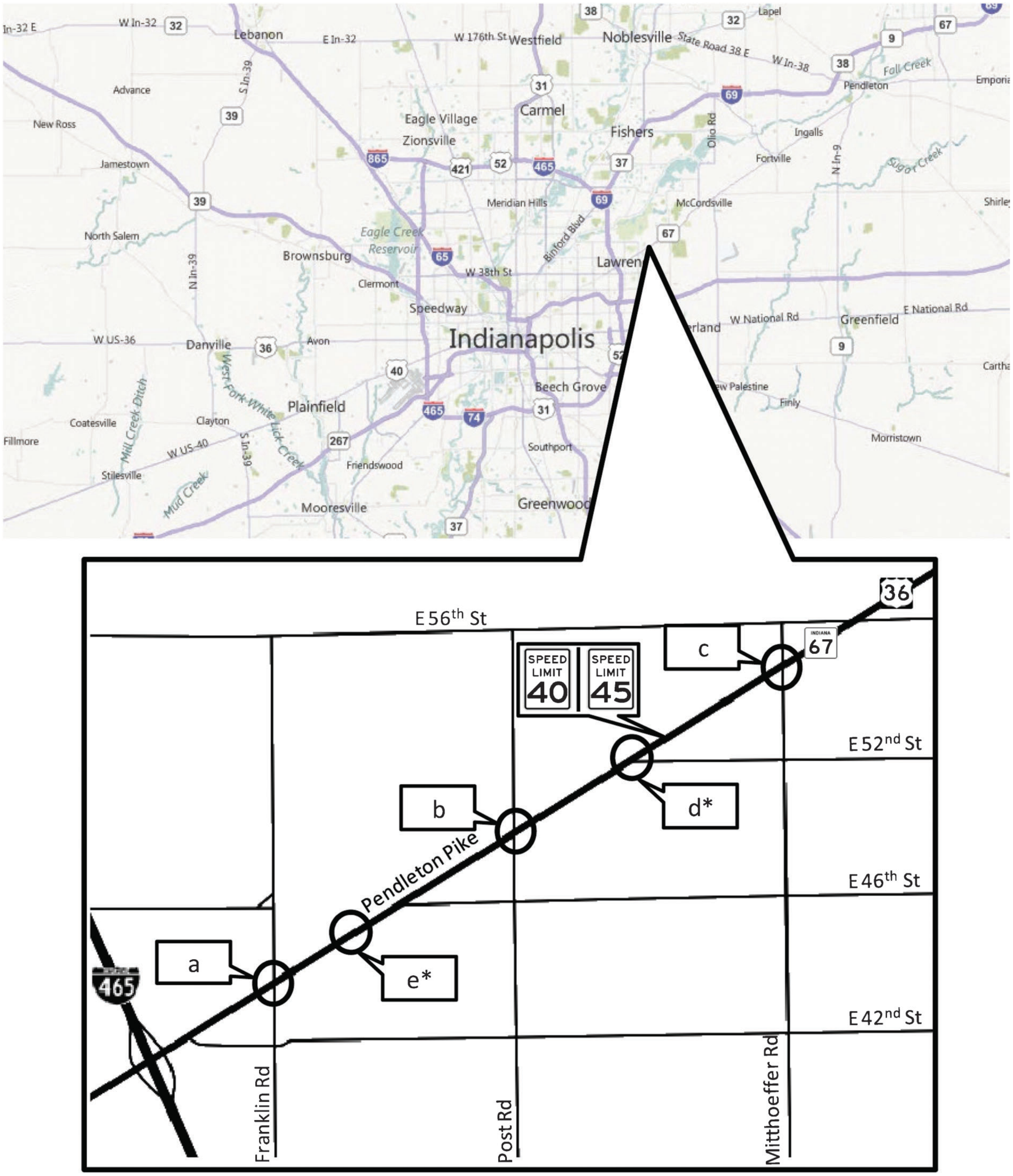


Figure 1.2 Signalized arterial (US 36 in Indianapolis, IN) used to conduct probe vehicle re-identification system (map obtained from www.bing.com). Figure reproduced from Remias et al. (14). * Indicates there is no magnetometer array at these intersections.

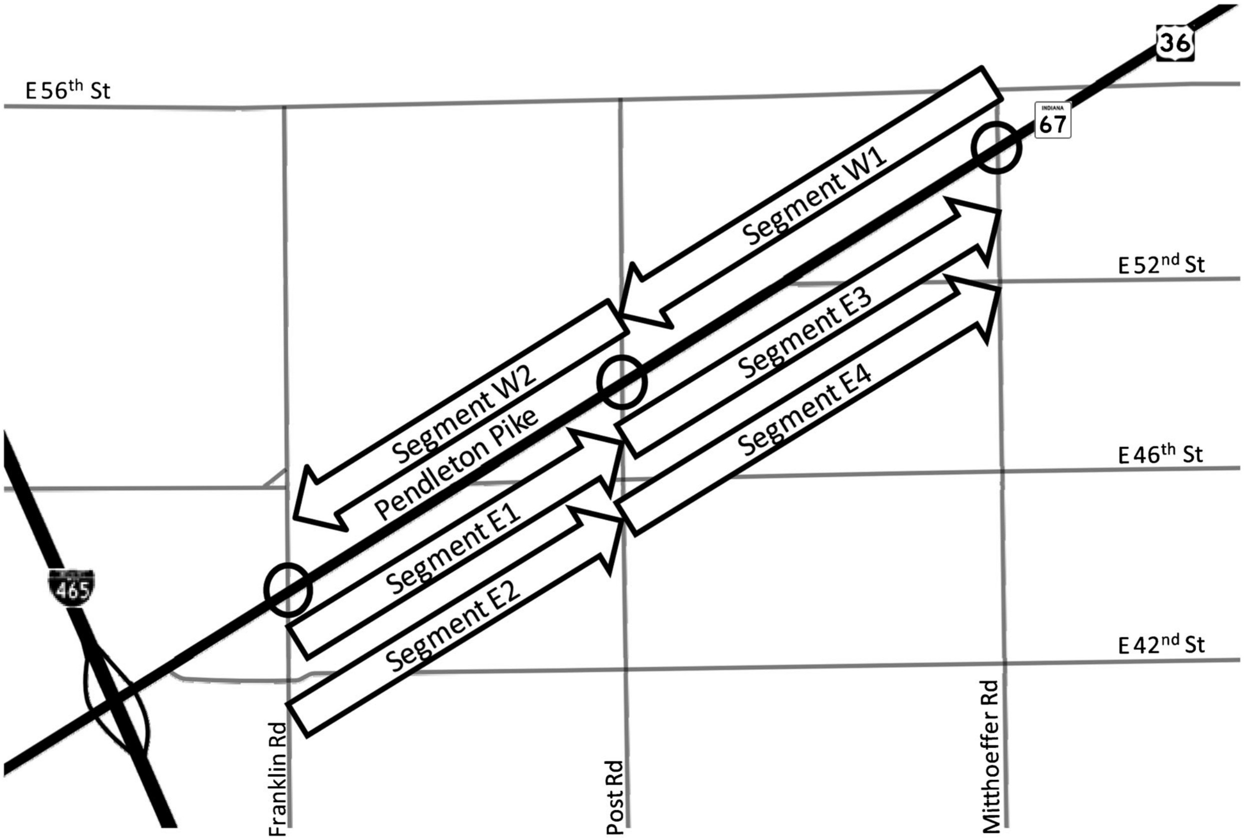


Figure 1.3 Travel time segments to be obtained from Sensys installation on US 36. Figure reproduced from Remias et al. (14)

for detection at an intersection. The intersection configuration used to estimate these costs is shown in Figure 1.1. This design contains four sets of advance detectors and eight lanes of stop bar detection. For this detector configuration, a savings of approximately $40,000 over 10 years is realized by using wireless magnetometers. Much of the savings can be attributed to the use of wireless connectivity for the detection rather than the conduit, handholds, and detector housing required for inductive loops. These estimated costs are current as of 2011. Because wireless magnetometers are a relatively new technology, it is possible to speculate that as wireless magnetometer sales volumes grow, the costs of components may decrease further. The results of this report find that, with appropriate detection zone specification, wireless magnetometers can deliver vehicle detection performance of similar quality to inductive loops.

1.5. Closing Comments

Despite nearly 350,000 signalized intersections in the United States, technology innovation in the traffic signal field has been somewhat sluggish over the past 50 years. This is due in large part to 50 states having 50 different standards, not to mention larger local agencies such as Los Angeles, Chicago, etc. add further fragmentation. Perhaps surprisingly, there has been very little national consensus on objective sensor testing. Indiana has emerged as a national leader in the evaluation9 of traffic signal detection technology and application of that technology for traffic signal operations and performance measures.

Over the past five years, INDOT's investment in this area and efforts to disseminate research findings has resulted in six national best paper awards, four from TRB (1,5,9,19), one from ASCE (18), and one from ITE (2). Although not all of those papers were the result of JTRP projects, they all benefited substantially from the instrumented intersections and corridors that INDOT has invested in so that "INDOT does not have to model what it can measure."

Lastly, Indiana is emerging as national leader in the area of traffic detection and traffic signal system performance measures. The noteworthy aspect of this is the opportunity for industrial partner to help fund significant infrastructure upgrades to the US 36 corridor (Figure 1.2) and labor required to conduct an evaluation of emerging technology to collect probe data travel time along the segments shown in Figure 1.3 (14).

CHAPTER 2. SPECIFICATION FOR DETECTOR PERFORMANCE

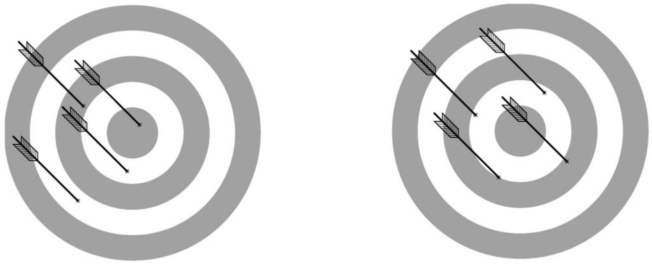
2.1. Objective

To develop a selection of vehicle detector types that are to be considered acceptable for procurement and installation, it is necessary to establish a standard method for judging whether a detector type should be accepted. The concept of a performance specification for vehicle detectors was pursued by research that was jointly pursued by Indiana using resources available through SPR-3206, and by individuals at the Texas Transportation Institute. The findings of this research were published in 2009 in *Transportation Research Record* (15). This research paper is summarized in this chapter, and a reprint is provided for project reviewers in Appendix A.

2.2. Motivation

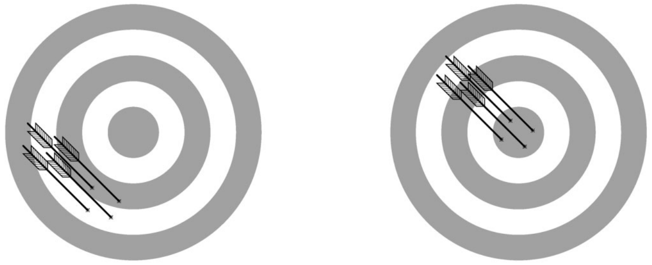
Vehicle detectors are used for several purposes. The most common use is to actuate a traffic signal to provide a call for an actuated vehicle phase, and to extend the green time of that phase based upon vehicle presence and/or volume-density timing logic. Historically, inductive loop detectors (ILDs) have been the most widely used technology for these applications. In recent years, new technologies that have arisen that promise various benefits such as easier installation and maintenance. These detection systems are usually compared with inductive loop detectors to establish a means of comparing performance. Writing a performance specification for new detection systems based on ILD performance (for example, specifying that the new system should meet or exceed the capabilities of ILDs) fails to take into account differences between detection technologies. More detailed performance criteria are needed to establish a fair set of criteria for acceptance.

Detector performance may be conceptually defined as having two dimensions, *precision* and *accuracy*. These concepts are illustrated in Figure 2.1, which shows arrows striking a target under various conditions of precision and accuracy. In Figure 2.1a, we see the obviously undesirable condition of an imprecise and inaccurate system. Figure 2.1b illustrates the performance of a system having accuracy but lacking precision; although many of the arrows are generally in the right location, the procedure is inefficient. Likewise, in Figure 2.1c, where the system is precise but lacks accuracy, the results of our efforts are unfavorable. Figure 2.1d illustrates the preferred situation where the system has both accuracy and precision.



(a)
Inaccurate and Imprecise

(b)
Accurate but Imprecise



(c)
Precise but Inaccurate

(d)
Accurate and Precise

Figure 2.1 Precision and accuracy. (a) Inaccurate and imprecise. (b) Accurate but imprecise. (c) Precise but inaccurate. (d) Accurate and precise

2.3. Findings

Two sets of performance criteria for detector acceptance are proposed, based on tolerances for applications specific to traffic signal actuation and green time extension. The first set of criteria concerns detector precision, and is based on the concept of detector *latency*, or the difference in time between when the detection zone enters a new occupancy state, and when the detection system reports that it occurs. Activation latency is the time difference for detecting a vehicle entering the detection zone, while termination latency is the time difference for returning to the unoccupied state when the vehicle leaves the detection zone. Activation and termination latency might have different characteristics depending on the detection technology.

The detector latency acceptance criteria specified by INDOT is summarized by Table 2.1. Detector precision is defined as tolerances for both the spatial and temporal edges of the detection zone. This table contains alternative tolerances for "low performance" and "high performance" operations depending on the criticality of the detector function. These are defined in terms of the 85th and 100th percentiles of observed latencies, which accounts for the fact that detector performance may tend to vary stochastically. In addition to these criteria, a maximum acceptable tolerance for false calls is proposed.

The second set of criteria is based on whether accurate vehicle calls are produced by the detection technology. The frequency of undesirable operational conditions is considered, namely the number of missed calls and false calls. A *missed call* is defined as any time when the detector fails to detect a vehicle, while a *false call* occurs when the detector reports a vehicle detection while a vehicle is not present.

Table 2.2 contains INDOT's specified acceptance criteria as the maximum number of missed and false calls that are within acceptable limits for operation

TABLE 2.1
Parameters for measuring detector performance (per respective detection zone) defined by Indiana Department of Transportation ITM No. 934-08P. Table reproduced from Middleton et al. (15)

	Low Performance		Standard Performance	
Test Parameter	During Amber and Red Interval	During Green Interval	During Amber and Red Interval	During Green Interval
Activation Position, Upstream Tolerance (A_u-A)	≤6.0ft	≤6.0ft	≤6.0ft	≤6.0ft
Activation Position, Downstream Tolerance (A-A_d)	≤6.0ft	≤6.0ft	≤6.0ft	≤6.0ft
Termination Position, Upstream Tolerance (T_u-T)	≤6.0ft	≤6.0ft	≤6.0ft	≤6.0ft
Termination Position, Downstream Tolerance (T-T_d)	≤6.0ft	≤6.0ft	≤6.0ft	≤6.0ft
Activation Response Time, Typical ($R_{a85\%}$)	≤2 sec	≤1 sec	≤1 sec	≤100 ms
Activation Response Time, Maximum ($R_{a100\%}$)	≤10.0 sec	≤5.0 sec	≤5.0 sec	≤1.0 sec
Termination Response Time, Typical ($R_{t85\%}$)	≤2 sec	≤1 sec	≤1 sec	≤100 ms
Termination Response Time, Maximum ($R_{t100\%}$)	≤10.0 sec	≤5.0 sec	≤5.0 sec	≤1.0 sec
False Call Duration (F_d)	≤5.0 sec	≤5.0 sec	≤500 ms	≤500 ms

TABLE 2.2
Acceptance criteria (per detection zone) defined by Indiana Department of Transportation ITM No. 934-08P. Table reproduced from Middleton et al. (15)

Test Criterion	Performance During Amber and Red Interval	Performance During Green Interval
Number of Missed Calls (N_{mc24}) in 24 hrs	0	≤10
Number of Missed Calls (N_{mc01}) in 1 hr	≤0	≤10
Number of False Calls (N_{fc}) in 24 hours	≤20	
Number of False Calls (N_{fc}) in 24 hours	≤20	

within any 24-hour or 1-hour time period. The number of missed calls is considered separately for red/amber and green intervals for actuated signal operations.

In addition to INDOT's specifications, research using a video detection system in Texas led to an alternative set of acceptance criteria based on the expected capability of a well-calibrated video detection system. These are described in more detail in Appendix A.

2.4. Implementation of Results

The findings of this research have been used by INDOT to define detector performance acceptance criteria to include a detector type on the approved materials list. The performance criteria were directly applied to the evaluation of wireless magnetometers during SPR-3206, which is described in the next chapter.

CHAPTER 3. OPERATIONAL EVALUATION OF WIRELESS MAGNETOMETERS

3.1. Objective

Wireless magnetometers are a minimally intrusive vehicle detection technology which contains a compact magnetic sensor and a battery power supply contained within an isolated unit. This unit is installed in the pavement to establish a detection zone, and wireless communications are used to transmit the detector state for use in signal control or other applications. In this research project, our objective was to determine whether this vehicle technology could be effectively used for the control of actuated phases at a traffic signal. An evaluation was conducted in 2008–2009, during which several lessons were learned regarding detection zone design. The findings of this research were published in 2010 in *Transportation Research Record* (16). This research paper is summarized in this chapter, and a reprint is provided for project reviewers in Appendix B. Additional material is included here regarding detection zone design and vehicle count performance.

3.2. Motivation

Inductive loop detectors (ILD) have been the most widely method of vehicle detection since their invention in the 1920s, because of their high performance reliability. However, ILD installation can be rather expensive, especially for advance detection, because of the need to install conduit to connect the loops back to the cabinet. While pave-over loops are a feasible option for unconstructed intersections, most loops are saw-cut. Saw-cut ILDs cannot be used for vehicle detection on areas such as bridge decks where pavement cuts cannot be made. Saw-cut ILDs are susceptible to failure, particularly if they are not well-sealed; gradual pavement damage caused by temperature variations and pavement loading also damages loops over time. The installation and maintenance of loops requires lane closure and, consequentially, delay to traffic.

Because of the costs and disadvantages associated with ILDs, INDOT has an interest in evaluating the performance of new detector technologies for possible inclusion as approved materials in intersection designs or improvements. Compact wireless magnetometers are a promising new detection technology offering several advantages. Because they are wireless and battery-powered, there is no need for installation of conduit to link the detectors to the cabinet. The small form factor of the detectors means that installation consists of a single coring operation, as opposed to the lengthy saw cuts typically required for ILDs. Installation requires less lane closure time than cutting new ILDs in the pavement, or installing and aiming (or re-aiming) video cameras on mast arms above the intersection. Photographs of a wireless magnetometer installation are shown in Figure 3.1.

Figure 3.2 shows a diagram of magnetometer installation at the test site. The components of the detection system are also explained in this diagram. The magnetometers are installed in the center of the lane in this test installation. To send the information back to the cabinet, radio frequency (RF) *repeaters* are installed on the roadside to amplify the signal. The *access point* is a device that collects the signals and transfers the information to the equipment in the cabinet. The access points can be installed on poles located adjacent to the street, eliminating the need for lane closures during that stage of the installation process. Example access point locations are shown in Figure 3.2.

In 2003, a prototype wireless magnetometer detection system was developed at the University of California Berkeley, which was then commercialized by Sensys Networks, Inc. Prior to the commencement of SPR-3206 in 2008, there had not yet been a rigorous, independent evaluation of Sensys wireless magnetometer performance for the purpose of vehicle presence detection at the stop bar of an intersection.

(a) Work zone set-up

(b) Drilling core for magnetometer

(c) Eliminating moisture in core void

(d) Placement of magnetometer

(e) Filling core void with epoxy

(f) Completed magnetometer installation

Figure 3.1 Wireless magnetometer installation. (a) Work zone set-up. (b) Drilling core for magnetometer. (c) Eliminating moisture in core void. (d) Placement of magnetometer. (e) Filling core void with epoxy. (f) Completed magnetometer installation

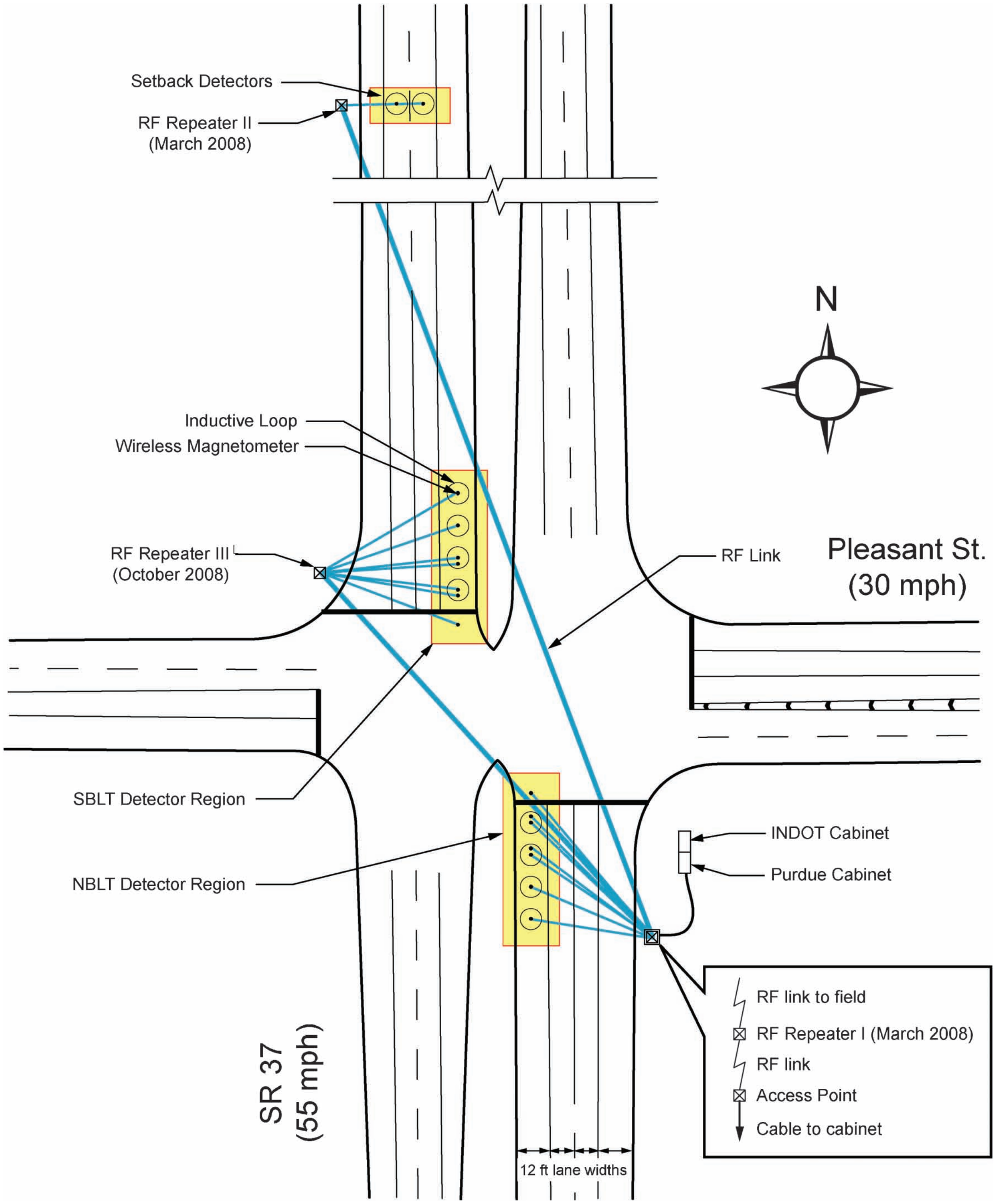


Figure 3.2 Intersection of detector evaluation test bed at SR 37 and Pleasant St., showing the locations of wireless magnetometers and access points. Figure reproduced from Day et al. (16)

3.3. Findings

A test bed for the evaluation was constructed in 2008 at the intersection of SR 37 and Pleasant St. in Noblesville, IN, as shown in Figure 3.2. This test bed includes both wireless magnetometers and ILDs within the same detection zone, while a video camera was used to obtain a record of vehicle presence. Two detection zones were installed. Discrepancies between the ILDs and the magnetometers were reconciled by visual inspection. Initial evaluations of the detection zone area led to several amendments to the initial design that are described later in this chapter. Full-scale detector evaluation was delayed by road construction, during which time project resources were used to define the performance acceptance criteria described in the previous chapter. Data collection for the evaluation took place in May-June 2009. Over 240 hours of data were included in the evaluation.

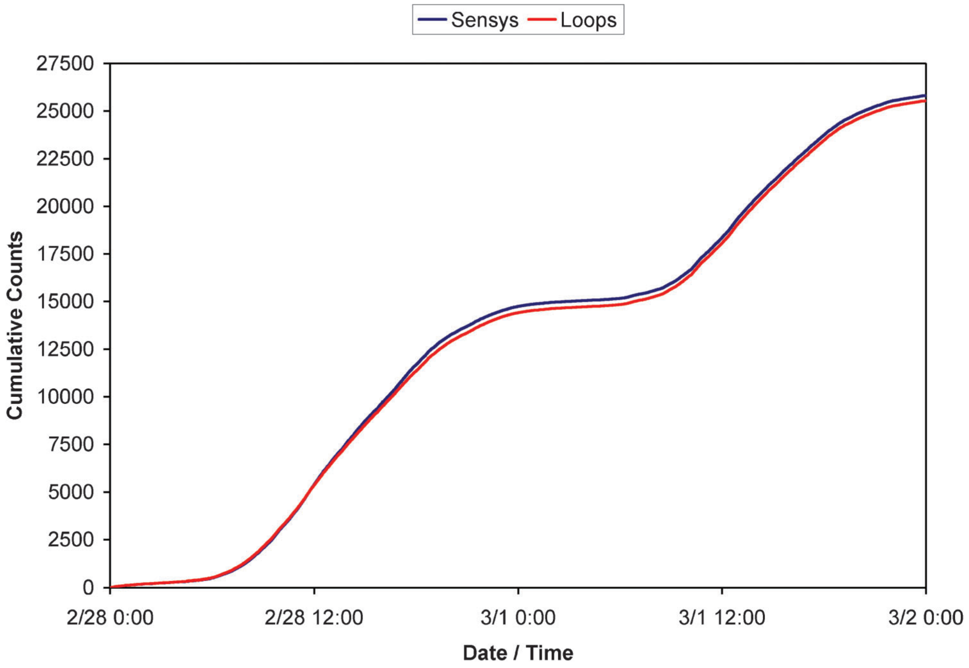


Figure 3.3 Cumulative counts over 48 hours from Sensys detectors and inductive loops. Data is from Feb. 28 and Mar. 1, 2009

In summary, the wireless magnetometers were found to operate within the accepted performance criteria defined in Table 2.1 and Table 2.2. The number of missed calls was similar to ILDs; a disproportionate number of undetected vehicles were motorcycles (with similar performance between both ILDs and wireless magnetometers). The magnetometers were found to produce slightly more false calls than inductive loops.

Magnetometer detection latency was found to be acceptable. The magnetometers performed well within the acceptance criteria for presence detection during the red/yellow interval. As for performance during the green interval, the magnetometers achieved acceptable performance for activation latency, which is the more critical aspect of latency for green extension. The magnetometers had average termination latencies slightly greater than the acceptance threshold.

In addition to these acceptance criteria, the performance of wireless magnetometers for vehicle counts was also evaluated. Magnetometers were installed in the center of the two setback ILDs located 405 ft upstream of the southbound approach of SR 37 and Pleasant St (one magnetometer per lane as shown in Figure 3.2). Plots of the cumulative counts over 48 hours from ILDs and wireless magnetometers are shown in Figure 3.3. The count was found to be in close agreement. Consequently, the difference in the counts varied with the traffic volume, but was less than 4% for an entire 24-hour period.

The minor differences in the counts are more likely to be due to the fact that the loops were “tied together” to form one detection zone spanning two lanes laterally, whereas the Sensys detectors provided individual counts per lane. ILD detection zones stretching across adjacent lanes typically under-count vehicles because if one vehicle enters lane A before while a vehicle is currently in lane B, the detection state does not get a chance to transition to an “OFF” state that would indicate a gap between vehicles.

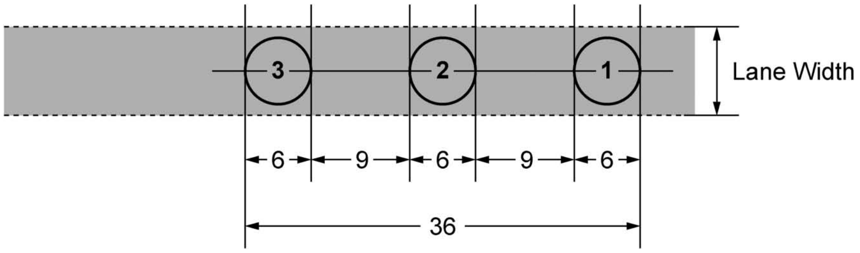
Proper detection zone design was found to be important. During this project, several lessons were learned regarding detection zone design, because of the limited prior knowledge regarding the use of wireless magnetometers for stop bar detection. The initial designs exhibited rather poor performance because they did not adequately cover the desired detection zone area. After revising the design, the performance was greatly improved. Based on these experiences, recommendations were given for detection zone design, as shown in Figure 3.4. Additional details regarding the detection zone design are included in Section 3.4.

3.4. Implementation of Findings

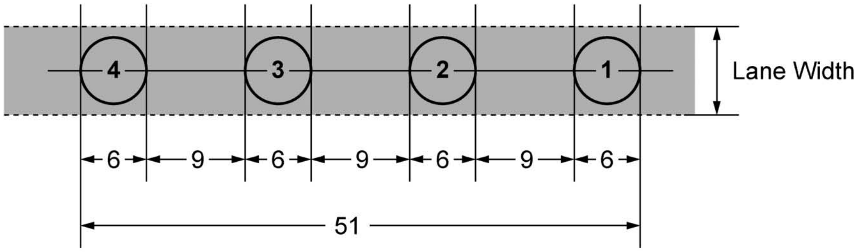
Wireless magnetometers have been used to control phase actuation and green extension for the northbound and southbound left turn phases at SR 37 and Pleasant St. since June 2009. Following the performance evaluation, the Sensys wireless magnetometer was subsequently added to the approved materials list. INDOT is currently working on developing a new standard specification for intersection detection that incorporates this type of detector.

3.5. Detection Zone Design Recommendations

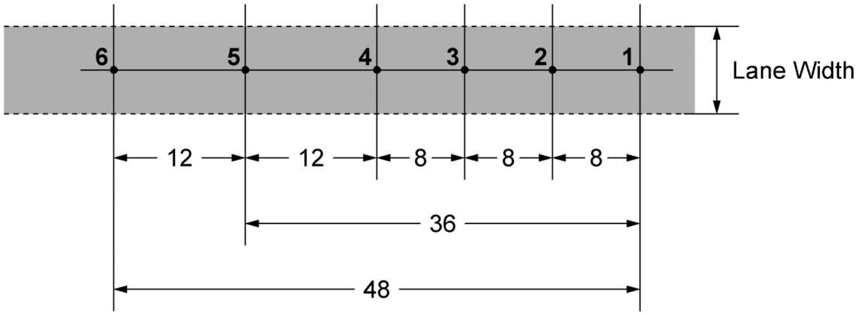
Figure 3.5 explains the fundamental difference between magnetometer and ILD response to vehicles.



(a) Three ILDs forming a 36 ft zone.



(b) Four ILDs forming a 51 ft zone.



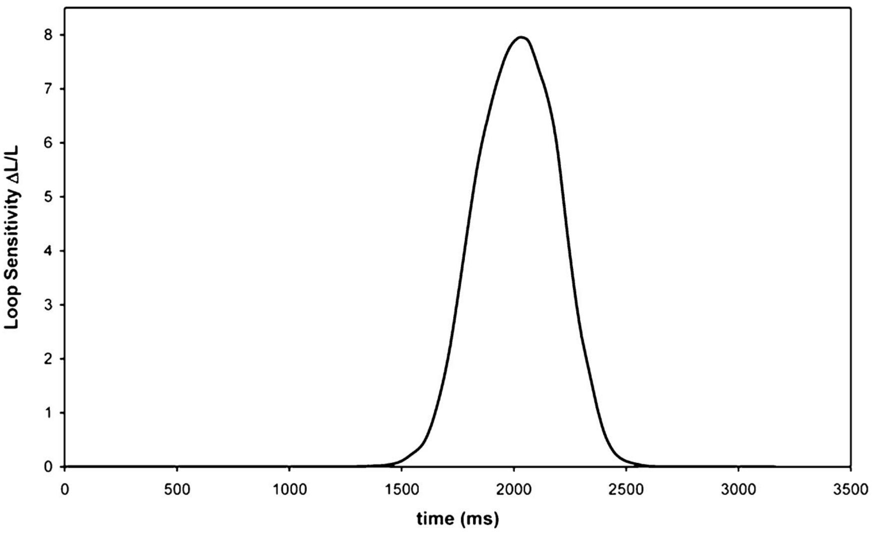
(c) Recommended installation of wireless magnetometers for a 48 ft detection zone.

Figure 3.4 Detection zone designs of various lengths (not to scale). Figure adapted from Day et al. (16). (a) Three ILDs forming a 36 ft zone. (b) Four ILDs forming a 51 ft zone. (c) Recommended installation of wireless magnetometers for a 48 ft detection zone

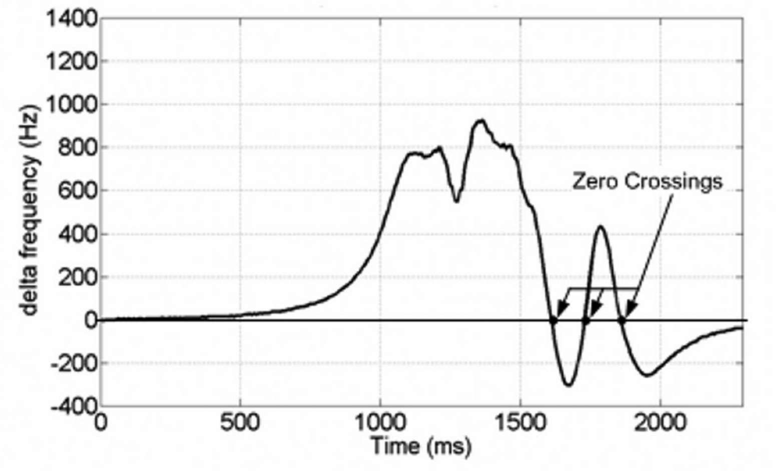
The graphs show the response of the detector types while a vehicle is moving across the detector. An inductive loop (Figure 3.5a) has a rather symmetrical response curve, and the magnitude of the change of inductance is always a positive number. In contrast, the response from a magnetometer (Figure 3.5b) has a characteristically unsymmetrical shape, and contains places where the magnitude of the response crosses the "zero" line and momentarily becomes negative. When the vehicle is positioned at a particular location, it can become invisible to this single magnetometer when the response curve is close to the zero crossing points. This was found to be a problem when using the magnetometers for presence detection, because some vehicles would stop in the "blind spot" of the individual detector and become undetected. Placing two detectors relatively close together (8 ft spacing was used in the SR 37 testbed, as shown in Figure 3.6) successfully eliminated this problem at the test site. Therefore, for the purpose of measuring vehicle presence, it is recommended to layer multiple sensors to eliminate blind spots in stop bar detection zones, as shown in Figure 3.4c.

Figure 3.6 shows two detection zone designs that were tested during the course of this research. The original detector design concept is shown in Figure 3.6a, where a single magnetometer was included at the center of each loop. This configuration was found to be inadequate because of the existence of blind spots. The detector configuration was subsequently changed to the setup shown in Figure 3.6b, which provides some overlapping magnetometer detection close to the stop bar.

Figure 3.7 shows the durations of potential false calls (Figure 3.7a) and missed calls (Figure 3.7b) from 24 hours of operation in the southbound left turn at SR 37 and Pleasant St. under the original design (shown in



(a) Typical ILD response curve.

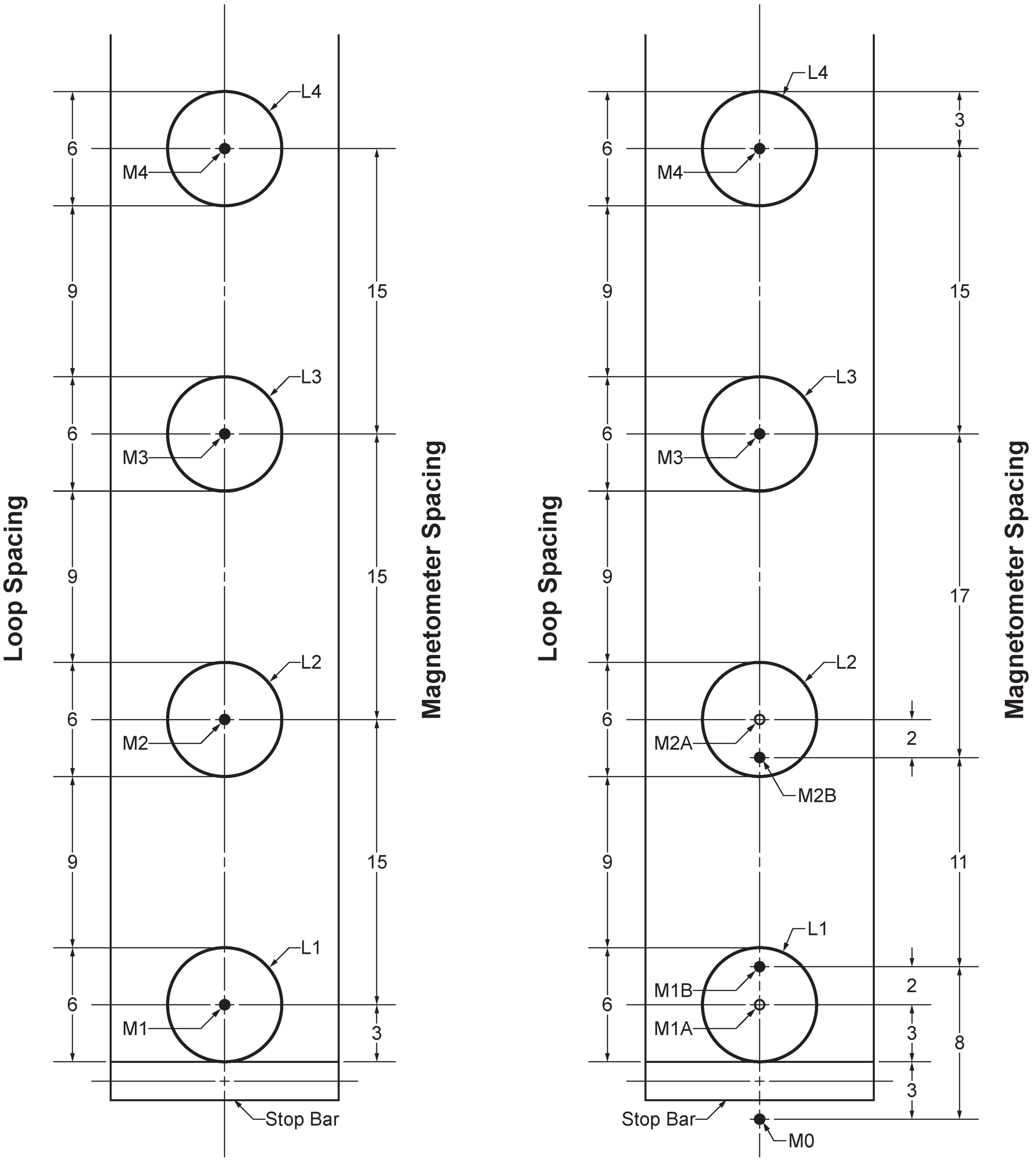


(b) Typical magnetometer response curve.

Figure 3.5 Comparison of example typical detector response for an ILD and a magnetometer. The magnetometer data is obtained from a conventional magnetometer. Figure reproduced from Day et al. (16). (a) Typical ILD response curve. (b) Typical magnetometer response curve

Figure 3.6a). Each line in these plots represents the duration of a single discrepancy between the ILD and the magnetometer occupancy states reported to the signal controller. The number of discrepancies is greatly reduced after detection zone was redesigned (shown in Figure 3.6b), as shown in Figure 3.8. There are considerably fewer false calls (Figure 3.8a), while there are practically no missed calls (Figure 3.8b). These results show that detection zone design is critical, and also that effective performance can be obtained from only two overlapping two magnetometers.

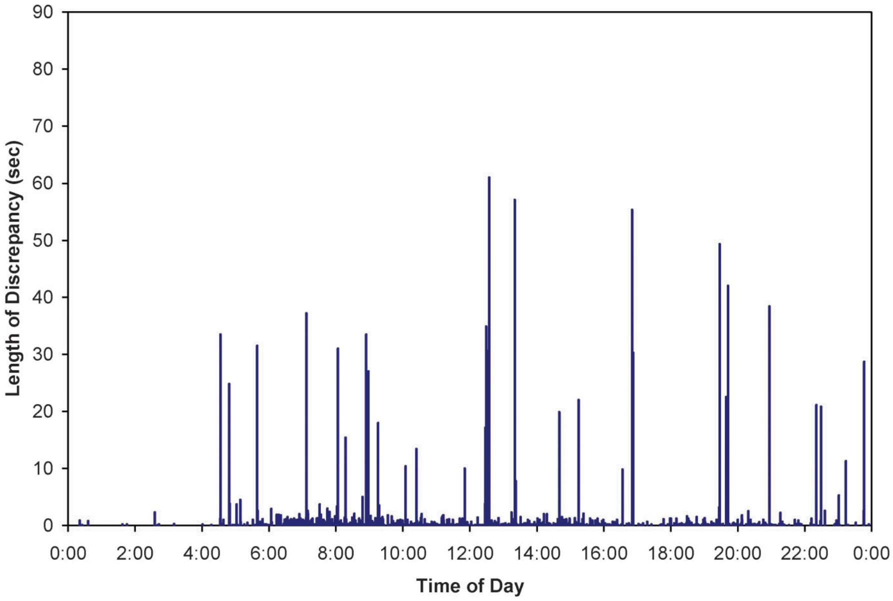
Motorcycle detection was a challenge for magnetometers, which is similar to the performance of other detection systems. For example, most ILDs do not detect motorcycles that are stopped in the middle of the lane, while they do detect motorcycles when their wheels are parked on the loop edges. In contrast, using wireless magnetometers in the middle of the lane path tends to miss motorcycles that do *not* stop in the middle of the lane. These problems might be alleviated by pavement marking to show motorcyclists where to stop to actuate the signal. Another potential solution might be to include perhaps two detectors next to each other laterally close to the end of the loop, but some care should be taken to avoid detecting vehicles in the adjacent lane.



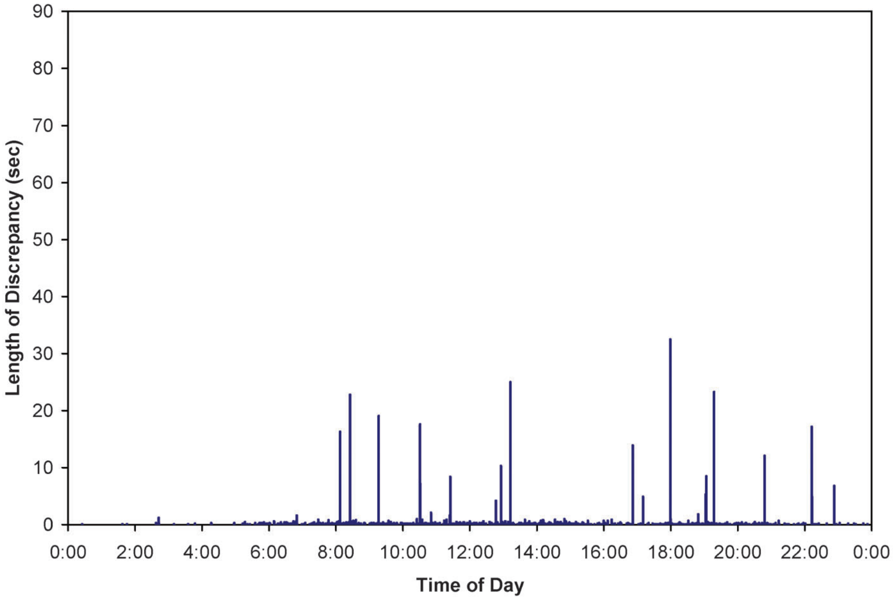
(a) Original NBLT installation.

(b) NBLT installation modified on March 25, 2009 by retiring sensors M1A and M2A and adding sensors M0, M1B, and M2B.

Figure 3.6 Testbed geometry and detector placement for left turn lanes. Figure reproduced from Day et al. (16). (a) Original NBLT installation. (b) NBLT installation modified on March 25, 2009 by retiring sensors M1A and M2A and adding sensors M0, M1B, and M2B

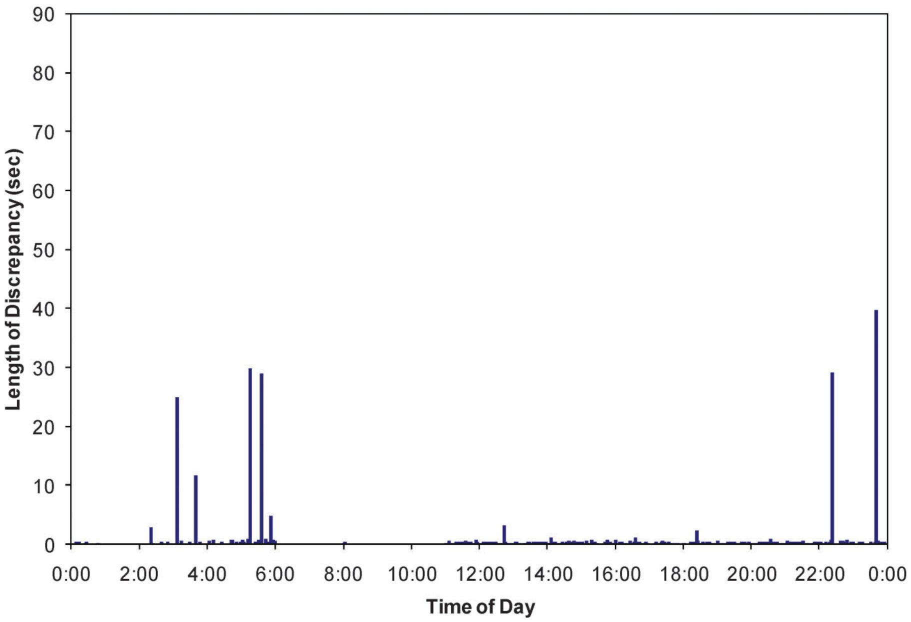


(a) Potential false calls(L0M1 discrepancies) from February 26, 2009.

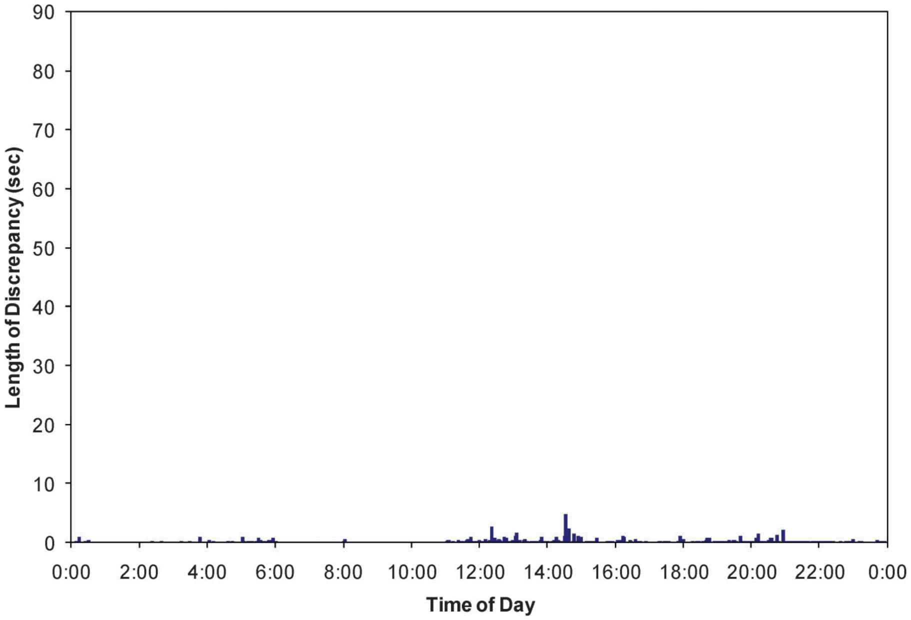


(b) Potential missed calls (L1M0 discrepancies) from February 26, 2009.

Figure 3.7 Discrepancy results from February 26, 2009 field test (initial installation). (a) Potential false calls (L0M1 discrepancies) from February 26, 2009. (b) Potential missed calls (L1M0 discrepancies) from February 26, 2009



(a) Potential false calls (L0M1 discrepancies) from May 28, 2009.



(b) Potential missed calls (L1M0 discrepancies)from May 28, 2009.

Figure 3.8 Discrepancy results from May 28, 2009 field test (revised detection zone). (a) Potential false calls (L0M1 discrepancies) from May 28, 2009. (b) Potential missed calls (L1M0 discrepancies) from May 28, 2009

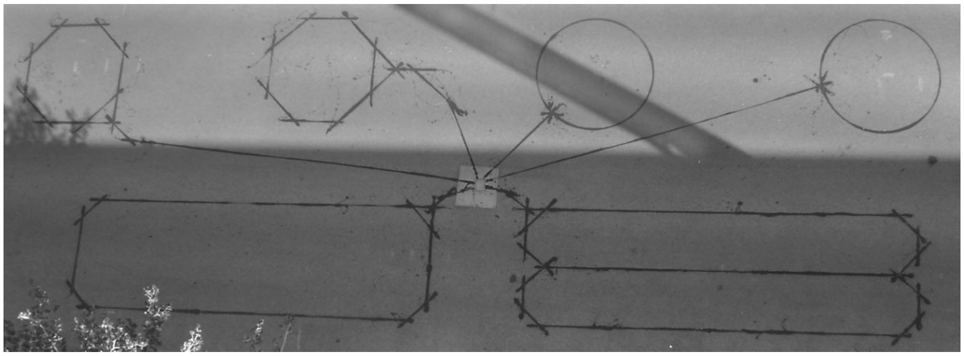


Figure 4.1 Loop detector test bed

CHAPTER 4. THREE-DIMENSIONAL MAPPING OF LOOP DETECTOR SENSITIVITY

4.1. Objective

Despite their use for over 80 years as the de facto standard method of vehicle detection, there is only a limited amount of literature regarding the responsiveness of alternative loop detector designs. Existing studies do not provide a comparison of the performance of alternative loop geometries. During the spring of 2008, research to characterize ILD performance was conducted while the testbed for magnetometer evaluation (described in the previous chapter) was under development. The findings of this research were published in 2010 in *Transportation Research Record* (17). This research paper is summarized in this chapter, and a reprint is provided for project reviewers in Appendix C.

4.2. Motivation

There is very little detailed empirical material available to traffic engineers regarding the specification of loop geometries. Most agencies have a set of accepted designs, and many engineers have opinions regarding the performance of various geometries and experience with their performance. Obviously, the standard designs work well for typical design vehicles (passenger cars and light trucks), as these have been widely used for many years. Problems with designs arise from exceptional cases, particularly vehicles with undercarriages that sit high above the pavement. It was not known how well different geometries would respond to vehicle bodies with varying amounts of vertical clearance. This study investigates this question and also provides numerous comparisons of the sensitivity of alternative geometries.

4.3. Findings

The response of several loop detector geometries was measured by directly recording the change in inductance resulting from moving sheets of metal across a loop at various lateral and longitudinal positions. An image of the loop detector test bed is shown in Figure 4.1, while a picture of a test in progress is shown in Figure 4.2. The test apparatus was constructed of non-metal components and capable of holding a sheet of metal at a fixed vertical position above the pavement. During this study, both steel and aluminum sheets were used to simulate the presence of a vehicle.

The most visually interesting results from this study are the three-dimensional plots of detector sensitivity, shown in Figure 4.3 and Figure 4.4. The response of various loop geometries to a galvanized steel sheet at 12 inches above the pavement are shown for a 20-ft quadrupole loop (Figure 4.3a), a 20-ft rectangular loop (Figure 4.3b), a 6-ft octagonal loop (Figure 4.4a), and a 6-ft round loop (Figure 4.4b). Figure 4.5 superimposes the cross sections of these four plots in a single graph.

The results of the study agreed with the theory of operation. Shorter vertical clearance and greater overlapping cross sectional area was found to increase loop response. There was no difference between the response from the aluminum and the steel sheets. With regard to loop geometry, there was essentially no difference

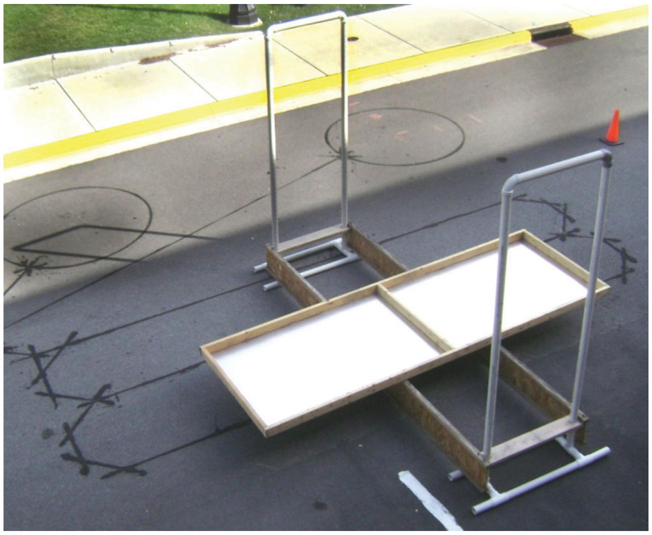
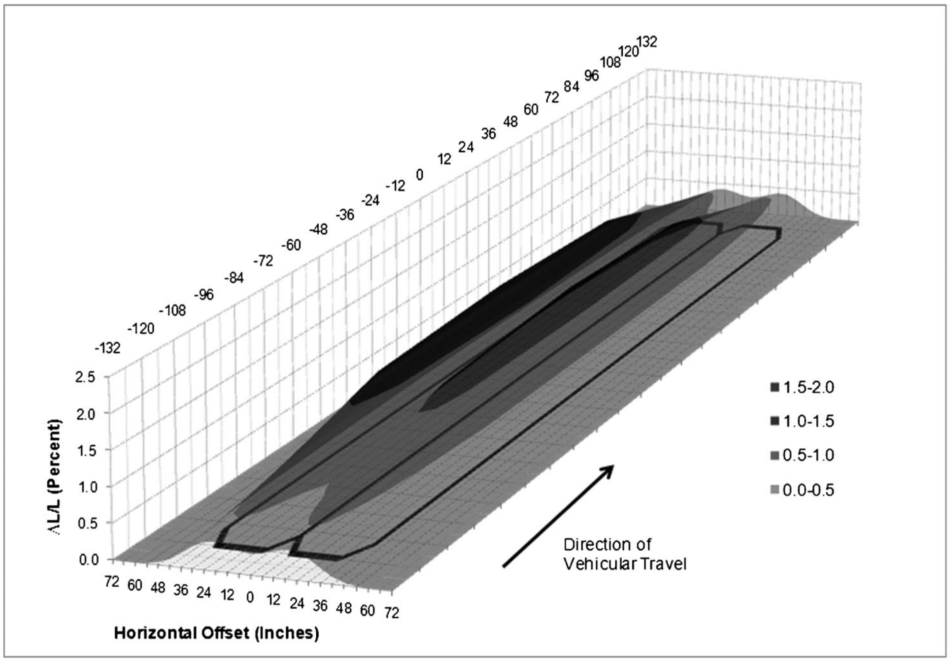
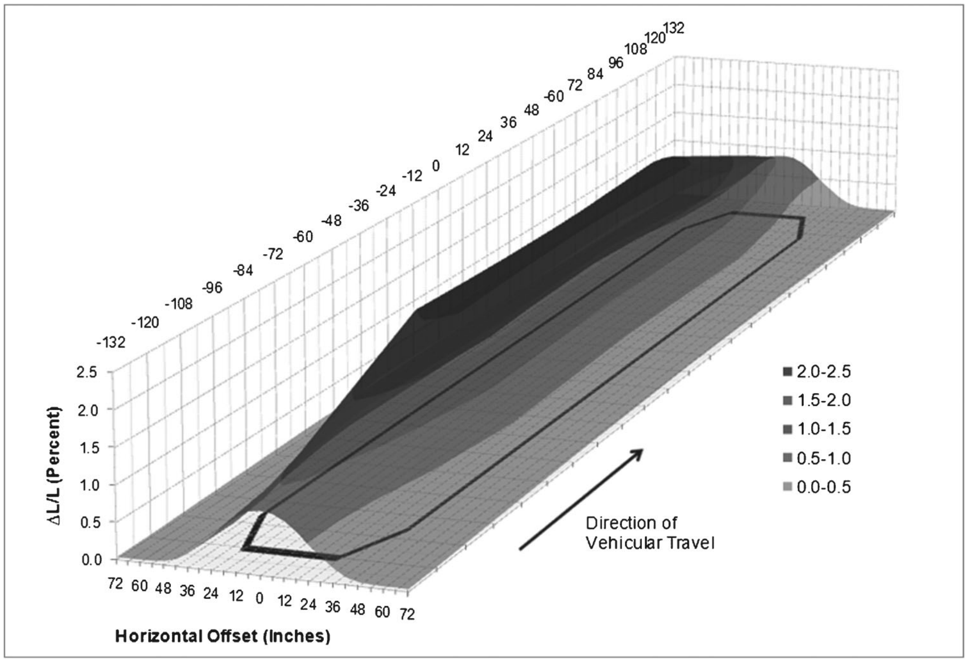


Figure 4.2 Test in progress



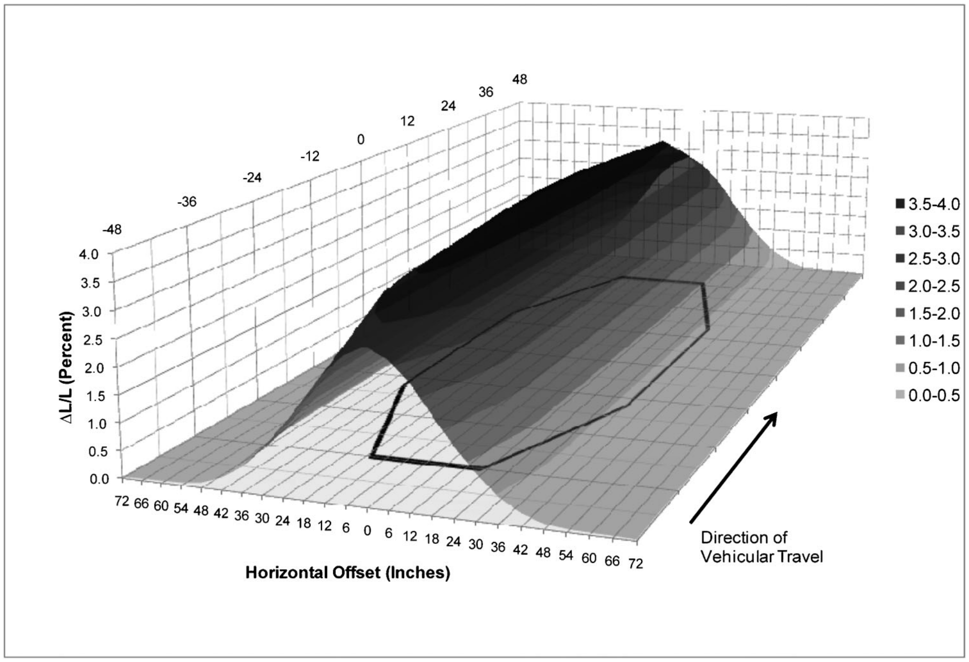
(a) 20 ftquadrupole loop.



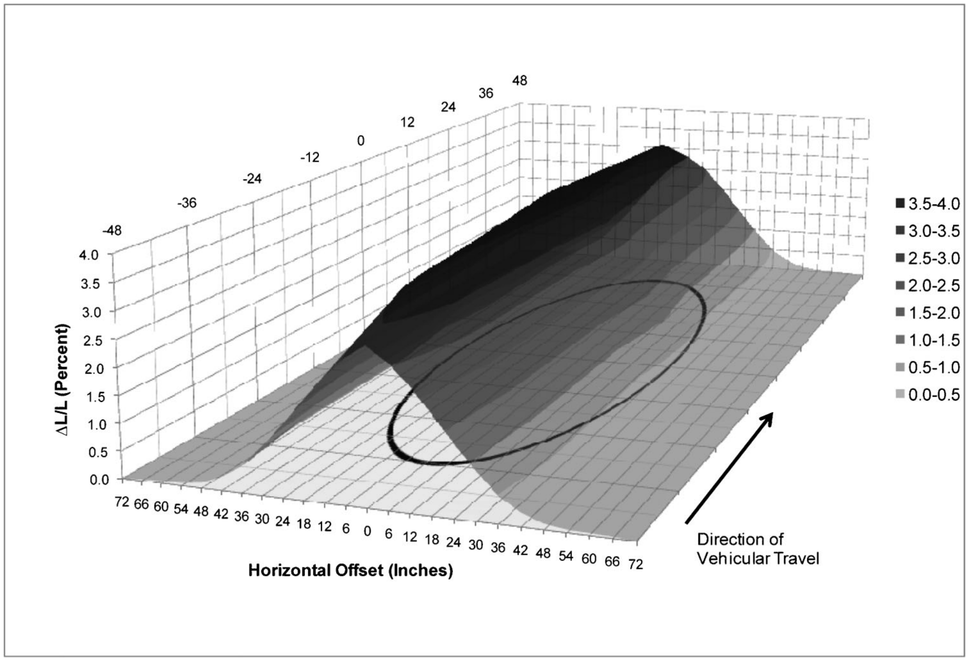
(b) 20 ft rectangular loop.

Figure 4.3 Three-dimensional plots of inductance response to the galvanized steel sheet elevated 12 inches from the pavement. Figure reproduced from Day et al. (17). (a) 20 ft quadrupole loop. (b) 20 ft rectangular loop

between the round and octagonal loops. The results for quadrupole loops were rather surprising. Quadrupole loops were found to be less sensitive than rectangular loops, which is contrary to the expectation that they should have greater sensitivity because of the central wire. Figure 4.6 conceptually illustrates the difference between the anticipated response and the measured response. Although quardupole loops offer the advantage of providing greater sensitivity to vehicles such as bicycles and motorcycles stopped in the center of a lane, the tradeoff is that they have reduced sensitivity to vehicles with greater vertical clearance.



(a) 6 ft × 6 ft octagonal loop.



(b) 6 ft round loop.

Figure 4.4 Three-dimensional plots of inductance response to the galvanized steel sheet elevated 12 inches from the pavement. Figure reproduced from Day et al. (17). (a) 6 ft × 6 ft octagonal loop. (b) 6 ft round loop

4.4. Implementation of Findings

These findings are relevant to detector zone design, or sensitivity settings, in situations where detection of vehicles with large vertical clearance is a concern. One example would be the detection of wooden horse-drawn carriages, which are still common in certain regions of the country. At lower sensitivity settings, quadrupole loops in particular may not detect these types of vehicles. Additionally, the findings of this study show that none of the four loop geometries have any special properties regarding sensitivity to adjacent lanes; response from the “edge” regions of all four loops were virtually identical.

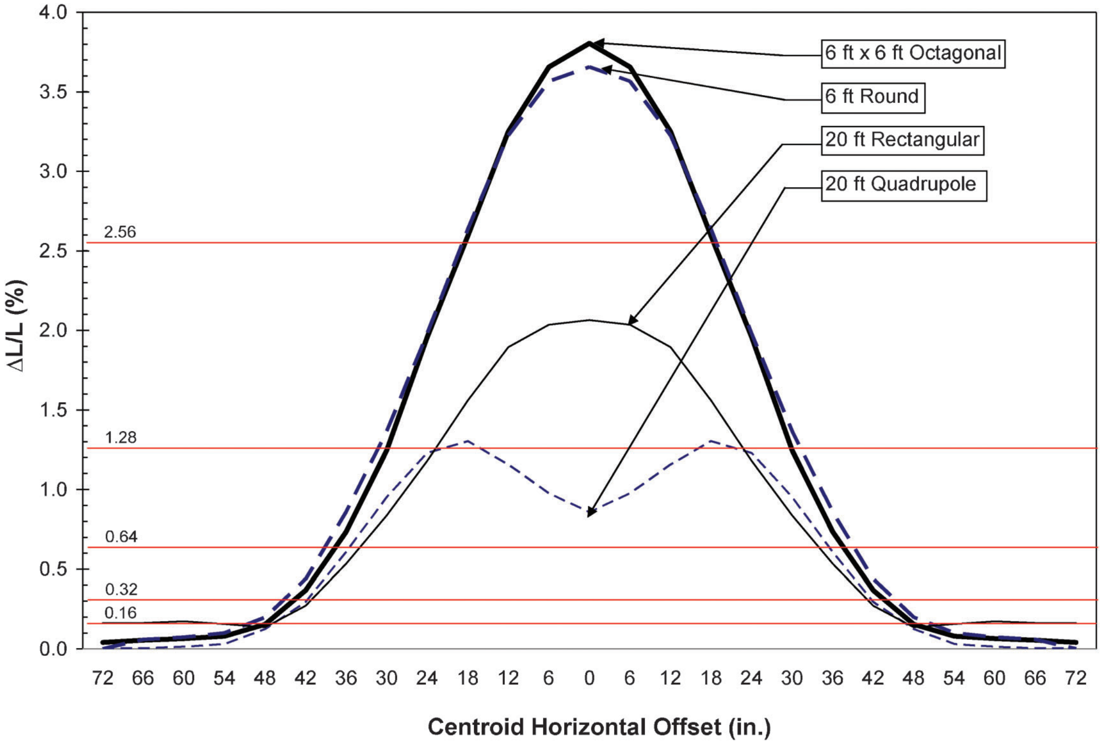


Figure 4.5 Comparison of loop response to galvanized steel at 12 inches above the pavement. Note that the 6 ft loop traces represent the sensitivity of a single loop; multiple loops in series would have an overall lower sensitivity. Figure reproduced from Day et al. (17)

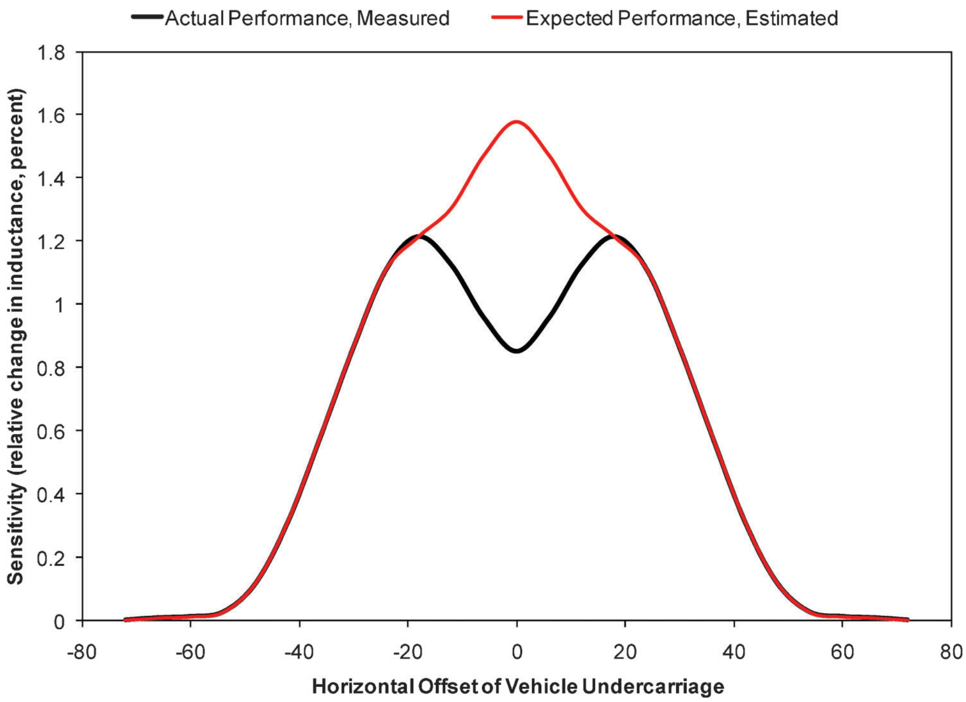


Figure 4.6 Expected and actual performance of quadrupole loops (quadrupole loop sensitivity measured using 12-inch vertical offset)

CHAPTER 5. PRACTICAL METHODOLOGY FOR TRAFFIC CONTROLLER PARAMETER CONSISTENCY CHECKING

5.1. Objective

A typical traffic signal controller has over 135,000 parameters, of which approximately 74,000 are configurable (see rows 1 and 4 in Table 5.1). Perhaps surprisingly, there is no existing resource for defining the parameters that should be configured and assessed for consistency, from either the industry on a national scale or from any specific vendor. The objective of this research effort was to leverage the NTCIP communication specification to systematically extract all parameters from a series of controllers along a corridor, enumerate the parameters typically configured by INDOT, and develop procedures for systematically assessing the consistency (and valid ranges) of those parameters.

5.2. Motivation

A typical traffic signal controller has over 74,000 configurable parameters. Indiana typically changes about 3000 of those parameters to define communication channels, vehicle detector assignments, signal phase timing, and time-of-day coordination patterns (see row 10 in Table 5.1). These parameters can vary by corridor depending on the facility characteristics (see rows 13 and 16 in Table 5.1). Along a specific corridor, approximately 300–500 parameters may need to be adjusted for each intersection (Table 5.2 and Table 5.3). Incorrect configuration of any single parameter can potentially cause significant problems, particularly if one of these blunders occurs in a time-of-day feature such that the problem is only observable during a certain time of the day. An example of how a potential problem that can be detected by comparing parameters longitudinally between controllers on a corridor is provided in Table 5.4. Here, we see that the "phaseRedClear" parameter is set for phases 9 through 16 for intersections 1–5, but not set for 6–22. Although this particular example is unlikely to cause any operational problems, it characterizes the types of inconsistencies that can occur in the configuration of controllers along a corridor. Some examples of inconsistencies that would cause operational problems would include mismatched cycle lengths, time-of-day pattern change times; errors in these parameters would prevent signals from being effectively coordinated on a corridor.

5.3. Findings

Tables of signal parameters were populated by transferring each data element by walking the management information base (MIB) tree defined by the NTCIP protocol, including the base NTCIP tree as well as the vendor-specific nodes. This was done by systematically extracting each parameter by passing a battery of SNMP "get" commands over an FTP connection to a controller on the bench. This procedure could also be used to obtain settings from a controller in the field. To obtain parameters from 22 intersections in a corridor, the controller databases were downloaded as binary files, and then uploaded to the test controller.

This procedure is a scalable technique that INDOT (and other agencies) can use to define their design space for traffic signal timings and then systematically review those parameters and define individuals or groups within their organization that are responsible for the configuration (rightmost columns in Table 5.2 and Table 5.3, which would be assigned according to agency policy). This design space is quite diverse,

TABLE 5.1
Distinct parameters for 22 intersections, 5 isolated and 17 coordinated

Row	Parameter Types	Number of Distinct Parameters		MIB Groups	Standard or Vendor-Specific
1	All Records	135,980	100.0%	1496	Both
2	All Records	103,296	76.0%	957	Vendor
3	All Records	32,684	24.0%	539	Standard
4	Readable/Writeable Parameters	74,773	55.0%	746	Both
5	Readable/Writeable Parameters	61,545	45.3%	541	Vendor
6	Readable/Writeable Parameters	13,228	9.7%	205	Standard
7	Operationally Important R/W	72,656	53.4%	509	Both
8	Operationally Important R/W	59,928	44.1%	375	Vendor
9	Operationally Important R/W	12,728	9.4%	134	Standard
10	Typical Indiana Parameter Changes	2,817	2.1%	129	Both
11	Typical Indiana Parameter Changes	1,968	1.4%	90	Vendor
12	Typical Indiana Parameter Changes	849	0.6%	39	Standard
13	Indiana Changes (5 Isolated Intersections)	398	0.3%	2	Both
14	Indiana Changes (5 Isolated Intersections)	0	0.0%	0	Vendor
15	Indiana Changes (5 Isolated Intersections)	398	0.3%	2	Standard
16	Indiana Changes (17 Coord Intersections)	1617	1.2%	83	Both
17	Indiana Changes (17 Coord Intersections)	1151	0.8%	59	Vendor
18	Indiana Changes (17 Coord Intersections)	466	0.3%	24	Standard

TABLE 5.2

Vendor-specific (proprietary NTCIP node) parameter changes identified among 17 coordinated intersections in a single corridor

Parameter Name	*Count	Comment	Number of Changed Parameters	Responsibility for Defining*
asc3AddedInitialOption	256	4 Table(s) of 64	17	
asc3ByDetType	64	64 Table(s) of 1	36	
asc3CallOption	256	4 Table(s) of 64	75	
asc3CNA2Phases	1	BINARY/TEXT	1	
asc3crdForceOffAddInitial	1	BINARY/TEXT	1	
asc3crdInterconnectSource	1	BINARY/TEXT	1	
asc3crdUsePedTime	1	BINARY/TEXT	1	
asc3DayPlanActionNumber	800	16 Table(s) of 50	9	
asc3DetExtensionOption	256	4 Table(s) of 64	70	
asc3DetPhaseLockDet	4	4 Table(s) of 1	1	
asc3DetPhaseMaxRecall	4	4 Table(s) of 1	1	
asc3DetPhaseVehRecall	4	4 Table(s) of 1	1	
asc3FlashExitOverlapDelay	1	BINARY/TEXT	1	
asc3MMUColorChkDisableGrn	16	16 Table(s) of 1	6	
asc3MMUColorChkDisableRed	16	16 Table(s) of 1	2	
asc3MMUColorChkDisableYel	16	16 Table(s) of 1	6	
asc3MMUCompatibilityMode	1	BINARY/TEXT	1	
asc3MMUCompatibilityState	160	160 Table(s) of 1	21	
asc3MMUCompatibilityStatus	160	160 Table(s) of 1	21	
asc3NtcipDualEntry	1	BINARY/TEXT	1	
asc3NtcipPhaseEnable	1	BINARY/TEXT	1	
asc3NtcipRing1Phase	255	15 Tables of 16, 1 of 15	4	
asc3NtcipRing2Phase	255	15 Tables of 16, 1 of 15	8	
asc3PassageOption	256	4 Table(s) of 64	70	
asc3PhaseAddedInitial	64	4 Table(s) of 16	10	
asc3PhaseMaximum1	64	4 Table(s) of 16	56	
asc3PhaseMaximum2	64	4 Table(s) of 16	56	
asc3PhaseMaximum3	64	4 Table(s) of 16	20	
asc3PhaseMaximumInitial	64	4 Table(s) of 16	10	
asc3PhaseMinimumGreen	64	4 Table(s) of 16	56	
asc3PhaseOptions	64	4 Table(s) of 16	8	
asc3PhasePassage	64	4 Table(s) of 16	56	
asc3PhasePedestrianClear	64	4 Table(s) of 16	24	
asc3PhaseRedClear	64	4 Table(s) of 16	56	
asc3PhaseRedRevert	64	4 Table(s) of 16	50	
asc3PhaseSimultaneousGapPhases	16	16 Table(s) of 1	2	
asc3PhaseWalk	64	4 Table(s) of 16	24	
asc3PhaseYellowChange	64	4 Table(s) of 16	56	
asc3ptnActionPlan	120	120 Table(s) of 1	1	
asc3ptnPhaseSplit	1920	120 Table(s) of 16	32	
asc3ptnSequenceSelect	120	120 Table(s) of 1	5	
asc3seqBarrierTypeSel	16	16 Table(s) of 1	5	
asc3seqPhaseConcurrency	16	16 Table(s) of 1	16	
asc3tbCtlSequence	36	36 Table(s) of 1	5	
asc3tbDetLog	36	36 Table(s) of 1	5	
asc3tbExceptDayPlan	36	36 Table(s) of 1	3	
asc3tbExceptDOMOrDOW	36	36 Table(s) of 1	3	
asc3tbExceptFormat	36	36 Table(s) of 1	1	
asc3tbExceptMonth	36	36 Table(s) of 1	3	
asc3tbExceptWOMOrYear	36	36 Table(s) of 1	2	
asc3tbLPStatementSel	20000	100 Table(s) of 200	16	
asc3tbResetTimeHour	1	BINARY/TEXT	1	
asc3tbResetTimeMin	1	BINARY/TEXT	1	
asc3unitWarningGrpDisableMap	1	BINARY/TEXT	1	
asc3VehDetCallPhase	256	4 Table(s) of 64	34	
asc3VehDetDelay	256	4 Table(s) of 64	16	
asc3VehDetExtend	256	4 Table(s) of 64	11	
asc3VehDetFailTime	256	4 Table(s) of 64	64	
asc3VehDetOptions	256	4 Table(s) of 64	86	
Sum of Parameter Counts	27361	Sum of Changes	1151	

*to be determined by agency policy.

TABLE 5.3
Standard NTCIP 1202 parameter changes identified among 17 coordinated intersections in a single corridor

Parameter Name	Counte	Comment	Number of Changed Parameters	Responsibility for Defining*
channelControlSource	16	16 Table(s) of 1	4	
channelControlType	16	16 Table(s) of 1	4	
coordForceMode	1	BINARY/TEXT	1	
dayPlanHour	800	16 Table(s) of 50	5	
patternOffsetTime	120	120 Table(s) of 1	4	
patternSequenceNumber	120	120 Table(s) of 1	5	
phaseAddedInitial	16	16 Table(s) of 1	4	
phaseMaximum1	16	16 Table(s) of 1	8	
phaseMaximum2	16	16 Table(s) of 1	8	
phaseMaximumInitial	16	16 Table(s) of 1	4	
phaseMinimumGreen	16	16 Table(s) of 1	8	
phaseOptions	16	16 Table(s) of 1	8	
phasePassage	16	16 Table(s) of 1	8	
phaseRedClear	16	16 Table(s) of 1	8	
phaseRedRevert	16	16 Table(s) of 1	2	
phaseYellowChange	16	16 Table(s) of 1	8	
splitTime	1904	119 Table(s) of 16	32	
timebaseAscPattern	100	100 Table(s) of 1	1	
timeBaseScheduleDay	200	200 Table(s) of 1	199	
vehicleDetectorCallPhase	64	64 Table(s) of 1	34	
vehicleDetectorDelay	64	64 Table(s) of 1	16	
vehicleDetectorExtend	64	64 Table(s) of 1	11	
vehicleDetectorFailTime	64	64 Table(s) of 1	64	
vehicleDetectorOptions	64	64 Table(s) of 1	20	
Sum of Parameter Counts	3757	**Sum of Changes**	466	

*to be determined by agency policy.

covering both pattern-specific parameters such as cycle, offset, and split; general signal parameters such as yellow times; detector assignments; time-of-day schedule settings; controller parameters such as communications settings; and specialized controller functions such as preemption and priority.

The results shown in this chapter are based upon the 22 intersection US 30 corridor in Merrillville, Indiana, but the techniques are based upon standard SNMP messages that are vendor neutral, but comprehensively include all vendor specific parameters. In the case study analyzed, of the approximately 74,000 configurable parameters, each intersection has approximately 2000 vendor specific parameters configured and 1000 NTCIP 1202 compliant parameters configured (see rows 11 and 12, Table 5.1). Obviously, these numbers will vary by agency and the type of corridor, but this methodology will be invaluable for precisely defining vendor and contractor scopes of work in deploying modern traffic signal systems as well as performing longitudinal analysis to identify blunders and outliers in configured controller parameters. An example of the types and number of changes required for the 17 coordinated intersections (which is part of the 22 intersection study site) are shown in Figure 5.1 (standard NTCIP parameters) and Figure 5.2 (vendor-specific parameters).

5.4. Implementation of Findings

This research study directly led to creation of a software utility to perform the automatic download of settings using NTCIP. The methodology is being integrated into INDOT's signal systems management program. The methodology's primary use, maintaining corridor-wide and agency-wide parameter consistency, is highly relevant to this greater task by providing a tool for verifying that implemented settings match design settings. Furthermore, the tool would make it possible in future to systematically store multiple vendor controller parameters in a relational database, opening the door to future tools that would make it easier for system operators to check and alter parameters.

TABLE 5.4

Example of inconsistencies/differences in phase red clear across multiple intersections on US 30 in Merrillville, IN (data analysis on May 11, 2011)

	Parameter values by intersection for phase red clearance time (seconds)																								
	Isolated Intersections					Coordinated Intersections																			
Parameter Name*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Min	Max	Max – Min
phaseRedClear.1	1.0	1.0	1.0	1.0	1.0	1.8	1.0	3.1	2.0	2.0	1.5	2.0	1.5	2.0	0.0	0.0	1.5	1.5	1.5	1.5	1.0	1.5	0.0	3.1	3.1
phaseRedClear.2	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.4	1.5	1.8	2.0	1.8	2.0	2.0	3.0	2.5	2.0	2.0	2.0	2.0	1.5	1.8	1.4	3.0	1.6
phaseRedClear.3	2.1	2.1	2.1	2.1	2.1	0.0	1.0	0.0	0.0	0.0	1.0	0.0	1.5	1.5	0.0	0.0	2.0	1.5	1.5	0.0	1.0	1.0	0.0	2.1	2.1
phaseRedClear.4	2.1	2.1	2.1	2.1	2.1	1.5	1.5	3.4	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	1.8	1.5	1.5	1.5	0.0	3.4	3.4
phaseRedClear.5	1.0	1.0	1.0	1.0	1.0	1.8	1.0	3.1	2.0	2.0	1.5	2.0	1.5	2.0	0.0	0.0	1.5	1.5	1.5	1.5	1.0	1.5	0.0	3.1	3.1
phaseRedClear.6	1.0	1.0	1.0	1.0	1.0	1.5	1.5	1.4	1.5	1.8	2.0	1.8	2.0	2.0	3.0	2.5	2.0	2.0	2.0	2.0	1.5	1.8	1.0	3.0	2.0
phaseRedClear.7	1.0	1.0	1.0	1.0	1.0	0.0	1.0	0.0	0.0	0.0	1.0	0.0	1.5	1.5	0.0	0.0	2.0	1.5	1.5	0.0	1.0	1.0	0.0	2.0	2.0
phaseRedClear.8	2.1	2.1	2.1	2.1	2.1	1.5	1.5	3.4	2.0	2.0	2.0	2.0	2.0	2.0	0.0	3.0	2.0	2.0	1.8	1.5	1.5	1.5	0.0	3.4	3.4
phaseRedClear.9	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
phaseRedClear.10	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
phaseRedClear.11	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
phaseRedClear.12	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
phaseRedClear.13	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
phaseRedClear.14	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
phaseRedClear.15	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
phaseRedClear.16	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0

*the final digit represents phase number.

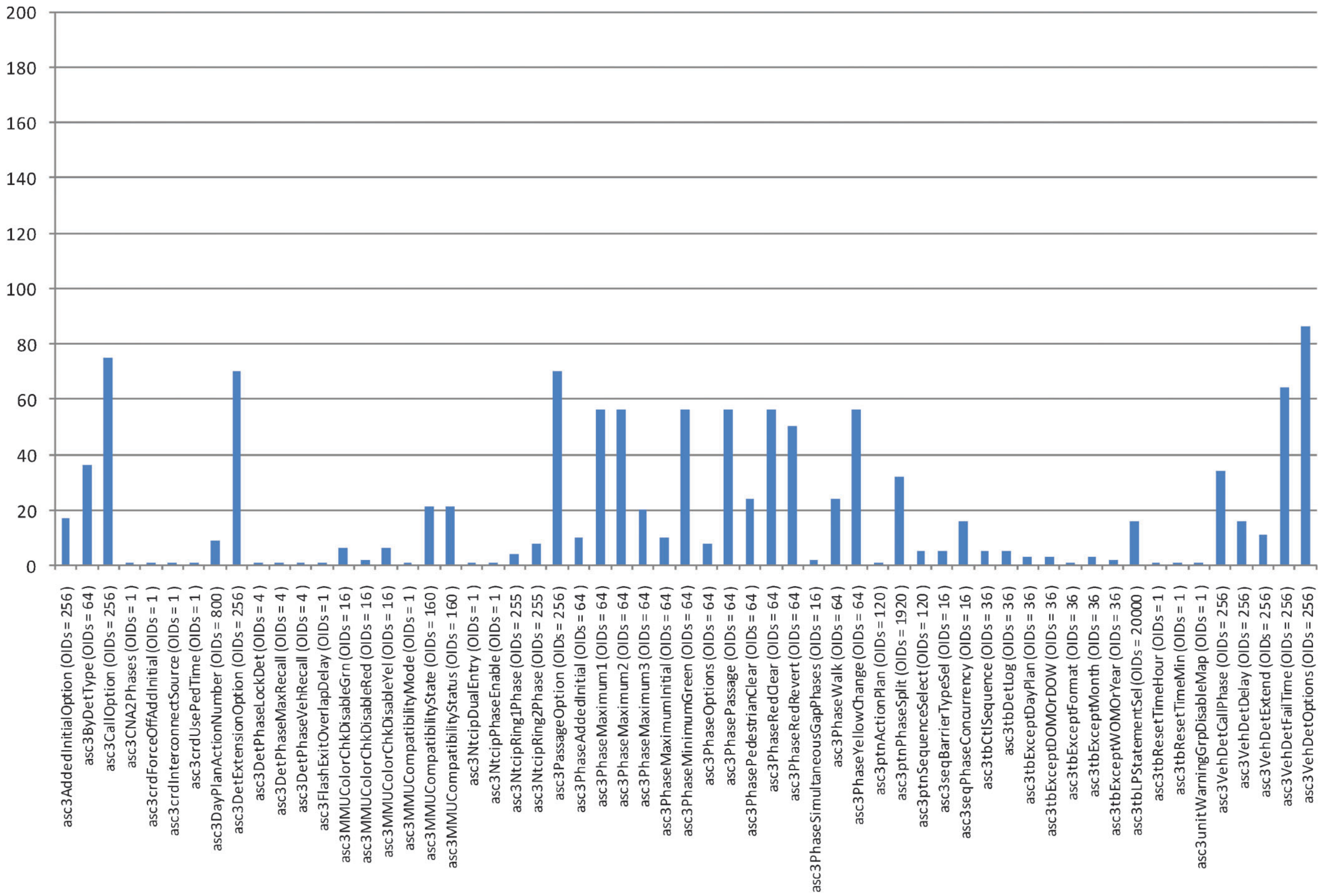


Figure 5.1 Vendor-specific parameters adjusted for 17 coordinated intersections along US 30 in Merrillville, IN. (Data analysis on May 11, 2011)

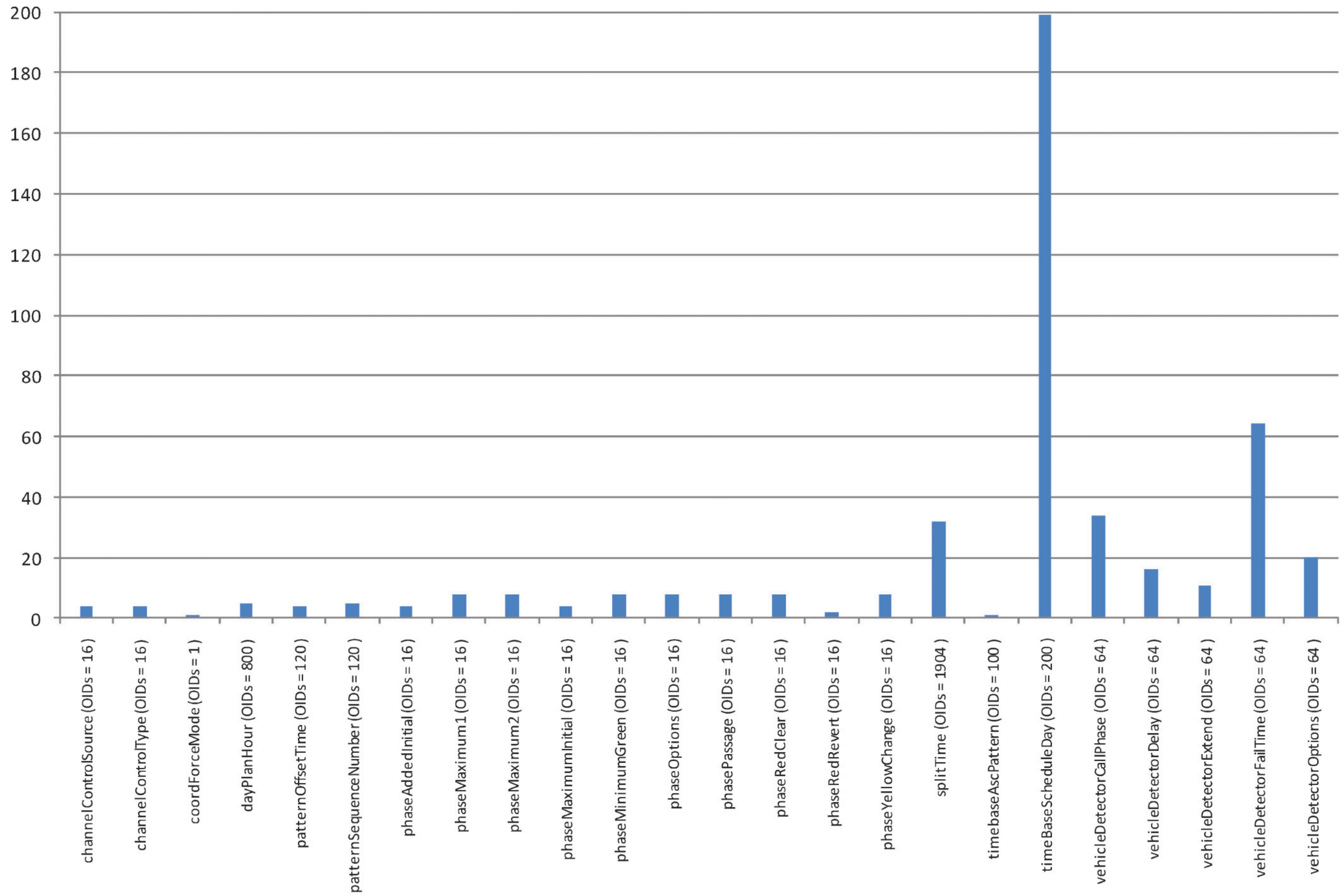


Figure 5.2 Standard NTCIP 1202 parameters adjusted for 17 coordinated intersections along US 30 in Merrillville, IN. (Data analysis on May 11, 2011)

APPENDIX A. PROPOSED CONCEPT FOR SPECIFYING VEHICLE DETECTION PERFORMANCE

Attached for SPR 3206 Study Advisory Committee:
Middleton, D., R. Longmire, D.M. Bullock, and J.R. Sturdevant, " A Proposed Specification Concept for Vehicle Detection," Transportation Research Record, #2128, TRB, National Research Council, Washington, DC, pp.161–171, 2009.
DOI: 10.3141/2128-17

APPENDIX B. OPERATIONAL EVALUATION OF WIRELESS MAGNETOMETER VEHICLE DETECTORS AT SIGNALIZED INTERSECTIONS

Attached for SPR 3206 Study Advisory Committee:
Day, C.M., H. Premachandra, T.M. Brennan, J.R. Sturdevant, and D.M. Bullock, "Operational Evaluation of Wireless Three-Axis Magnetometer Vehicle Detectors at a Signalized Intersection," *Transportation Research Record No. 2192*, Transportation Research Board of the National Academies, Washington, DC, pp. 11–23, 2010.
DOI: 10.3141/2192-02

APPENDIX C. THREE-DIMENSIONAL MAPPING OF INDUCTIVE LOOP DETECTOR SENSITIVITY WITH FIELD MEASUREMENT

Attached for SPR 3206 Study Advisory Committee:
Day, C. M., T.M. Brennan, M.L. Harding; H. Premachandra, A. Jacobs, D.M. Bullock, J.V. Krogmeier, and J. R. Sturdevant, " Three Dimensional Mapping of Inductive Loop Detector Sensitivity Using Field Measurement," Transportation Research Record, #2128, TRB, National Research Council, Washington, DC, pp.35–47, 2009.
DOI: 10.3141/2128-04

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