Evaluation of Non-Intrusive Technologies for Traffic Detection

Minnesota Department of Transportation

RESEARCH SERVICES

Office of Policy Analysis, Research & Innovation

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16. Abstract (Limit: 250 words)

The use of non-intrusive technologies for traffic detection has become a widespread alternative to conventional roadway-based detection methods. Many sensors are new to the market or represent a substantial change from earlier versions of the product. This pooled fund study conducted field tests of the latest generation of non-intrusive traffic sensors.

Sensors were evaluated in a variety of traffic and environmental conditions at two freeway test sites, with additional tests performed at both signalized and unsignalized intersections. Emphasis was placed on urban traffic conditions, such as heavy congestion, and varying weather conditions. Standardized testing criteria were followed so that the results from this project can be directly compared to results obtained by other transportation agencies.

While previous tests have evaluated sensors' volume and speed accuracy, the current generation of sensors has introduced robust classification capabilities, including both length-based and axle-based classification methods. New technologies, such as axle detection sensors, and improved radar, contribute to this improved performance.

Overall, the sensors performed better than their counterparts in previous phases of testing for volume and speed accuracy. However, the additional classification capabilities had mixed results. The length-based sensors were generally able to report accurate vehicle lengths. The axle-based sensors provided accurate inter-axle measurements, but significant errors were found due to erroneously grouping vehicles, affecting their ability to accurately classify trucks.

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EVALUATION OF NON-INTRUSIVE TECHNOLOGIES FOR TRAFFIC DETECTION
TPF-5[171]

FINAL REPORT

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LIST OF ACRONYMS

ADR	Automatic Data Recorder
ASTM	American Society for Testing and Materials
FHWA	Federal Highway Administration
GTT	Global Traffic Technologies, Inc.
Mn/DOT	Minnesota Department of Transportation
NIT	Non-Intrusive Technology
PLP	Piezo-Loop-Piezo
PNITDS	Portable Non-Intrusive Detection System
PVR	Per Vehicle Record
TAC	Technical Advisory Committee
TH	Trunk Highway
TIRTL	Transportable Infrared Traffic Logger
USB	Universal Serial Bus
VCU	Video Collection Unit

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EXECUTIVE SUMMARY

The third phase of the "Evaluation of Non-Intrusive Technologies for Traffic Detection" (NIT) project is a pooled fund study led by the Minnesota Department of Transportation (Mn/DOT), with technical guidance from the project's Technical Advisory Committee (TAC) and the Federal Highway Administration (FHWA). This phase of the project (TPF-5[171]) focused on conducting field tests of selected non-intrusive sensors to determine their accuracy for volume, speed and classification by length and classification by axle configuration. The project also identified deployment issues and costs associated with the technologies.

Sensors were evaluated in a variety of traffic and environmental conditions at two freeway test sites, with additional tests performed at both signalized and unsignalized intersections. Emphasis was placed on urban traffic conditions, such as heavy congestion, and varying weather and lighting conditions. Standardized testing criteria were followed so that the results from this project can be directly compared to results obtained by other transportation agencies. Appendix Table A1 documents these criteria.

Major findings for each of the five sensors included in this study are summarized below.

Wavetronix SmartSensor HD

- Speed and volume accuracy comparable to loops (typically within 1.6 percent for volume and less than 1 mph for speed), during both free flow and congested conditions.
- However, a per-vehicle analysis revealed some occlusion when slow moving trucks in the lane nearest the sensor blocked subsequent lanes, resulting in undercounting of about 20 percent in the occluded lanes, in periods of heavy congestion.
- Reported vehicle length with an absolute average error of 1.6 feet for passenger vehicles and 2.8 feet for large trucks.

GTT Canoga Microloops

- Volume and speed accuracy comparable to loops (typically within 2.5 percent for volume and less than 1 mph for speed), however, like loops, the sensor is susceptible to double counting due to lane changes.
- Reported vehicle length with an absolute average error of 3.7 feet for passenger vehicles and 4.0 feet for large trucks.
- Requires installation of two three-inch conduits under the roadway, which is typically bored in from the road shoulder. This installation can be done without intrusion onto the surface of the roadway.

AxleLight

- Axle-spacing accuracy was typically within 5 percent of the baseline spacing. Speed values were consistently 2 mph lower than baseline. The sensor typically undercounted by 5.4 percent, although additional corrections could improve the data, such as filtering out misclassified vehicles that were placed in a default class.
- Volume (and classification) accuracy was dependent on selecting a classification scheme that successfully matched detection events to actual vehicles due to the lack of a presence sensor between axle detections. In other axle-based classification systems, such as a

piezo-loop-piezo, the loop detects when there is a vehicle present over the sensor. Without a presence sensor to determine gaps between vehicles, closely spaced vehicles are easily grouped.

- One set of sensors can cover bidirectional traffic on divided roadways, but the crowns of each road must be close to the same elevation. This type of deployment takes additional time and iterative adjustments.
- Many steps are required to deploy and calibrate the sensor; required significant experience through trial and error to learn proper procedures.
- Limited locations for setup; requires guard rail or similar infrastructure to which the sensors can be attached.
- Installations have advantage of only requiring sensor deployment on one side of the roadway.
- Can be installed in a permanent location by placing the sensors in a specially-designed cabinet.
- Snow plowing can deposit snow on the sensors if they are located too close to the roadway. Placing the sensors further away can mitigate these issues, but snow accumulation in the path of the sensor's beams must still be considered.

TIRTL

- Speed and axle-spacing accuracy was typically within 2 percent.
- Volume (and classification) accuracy was dependent on selecting a classification scheme that successfully matched detection events to actual vehicles due to the lack of a presence sensor between axle detections. In other axle-based classification systems, such as a piezo-loop-piezo, the loop detects when there is a vehicle present over the sensor. Without a presence sensor to determine gaps between vehicles, closely spaced vehicles are easily grouped.
- One set of sensors covered four lanes of bidirectional traffic on a divided roadway.
- Portable deployment usually requires significant traffic control to protect field personnel and equipment, especially since work is required on both sides of the roadway (except in cases where work can be done behind guard rail). The level of traffic control varies depending on local regulations and the site layout.
- Can be installed in a permanent location by placing the sensors in a specially-designed cabinet.
- Snow plowing can deposit snow on the sensors if they are located too close to the roadway. Placing the sensors further away can mitigate these issues, but snow accumulation in the path of the sensor's beams must still be considered.

Miovision

- Volume accuracy matched the accuracy of manual count verification (typically within 2.2 percent).
- The system is primarily intended to provide volume data, but rudimentary classification data is also available. No speed data is reported.
- Per-vehicle records are not available.
- System is intended for turning movement counts at intersections, but may also be used for other count applications.

- Video files are submitted to the vendor for remote processing on a per-hour basis.
- Quick setup. May be installed on a pole or self standing on a tripod.

While previous tests have evaluated sensors' volume and speed accuracy, the current generation of non-intrusive sensors has introduced robust classification capabilities. New technologies, such as axle detection sensors, and improved radar, contribute to this improved performance.

The project found that classification analysis required time-consuming data scrutiny to match sensor data records with the baseline. This analysis revealed that when properly set up and configured, the sensors perform in accordance with vendor claims. However, when converting the data to a standardized classification scheme, such as FHWA's 13 class scheme, unintentional errors can be introduced. Agencies must perform independent analysis of their classification schemes to determine whether they will provide acceptable results without a presence sensor.

Overall, the sensors performed better than their counterparts in previous phases of testing for volume and speed accuracy. However, the additional classification capabilities had mixed results. The length-based sensors were generally able to report accurate vehicle lengths within their tolerances. The axle-based sensors provided accurate inter-axle measurements, but significant errors were found due to erroneously grouping vehicles, affecting their ability to accurately classify trucks. These factors resulted in large percent errors for 3-axle and 4-axle vehicles, but did not significantly affect the volume performance of other classes.

The table on the next page provides a high-level summary of the project's quantitative findings. ***Refer to the Results section of this report for detailed discussion and interpretation of these findings.*** The findings presented in this table are for testing at the NIT Test Site (three lanes, one direction) and TH 52 Test Site (four lanes with depressed median, bidirectional). These results may not apply to other sites with other lane configurations. The Test Methodology section further defines the specific test site conditions.

Test Results Summary Table (1)

Factor		Wavetronix SmartSensor HD	GTT Canoga Microloop	PEEK AxleLight	TIRTL	Miovision
Technology		Radar	Magnetometer	Laser	Infrared	Video
Mount		Side fire	Under road	Side fire	Side fire	Side fire
Volume Error	**LOS A-D**	<2%	2.5%	5.4%	3.8%	<2.0%
	LOS E-F	2 to 20% (2)	2.5%	N/A	N/A	<2.0% (3)
Speed Error	**LOS A-E**	<1 mph	<1 mph	2 mph	1.2 mph	N/A
Length or Axle-Spacing Measurement Error (4)	**LOS A-D**	1.6' to 2.0' (5)	3.7' to 4.0' (6)	1' to 2' (7)	<1.0' (7)	Not tested
Ease of Installation (Portable)		+	–	–	–	+
Ease of Installation (Permanent)		+	–	–	–	Not Applicable
Ease of Calibration		+	+	–	+	+
Performance in Heavy Rain		+	+	(8)	(8)	Not tested
Performance in Snow/Fog		+	+	(9)	(9)	Not tested
Approximate Cost (10) (Sensor System Cost Only)		$6,500	$4,000	$31,580	$21,475	$2,995(11)

Notes:

1. This table provides a high-level summary of the project results. Refer to the Results section of this report for detailed discussion and interpretation of these findings.
2. Error depends on the lane. It was found that far lanes experience error due to occlusion in congested conditions.
3. Level of Service (LOS) E-F for Miovision was tested at the intersection only.
4. Additional error may be introduced when vehicles are assigned to classes.
5. Physical length of vehicle.
6. Magnetic length of vehicle.
7. Axle spacing.
8. Vendor does not recommend data collection in heavy rain (defined as greater than 0.30 inches per hour).
9. Sensor susceptible to beam blockage by snow along side of roadway.
10. These costs were provided by the sensor manufacturers or vendors. Refer to the costs presented in the Results section for more information about each sensor.
11. The vendor charges per hour of video analysis. Cost varies by amount of data to be analyzed. As an alternative to purchasing the sensor, it can be rented from the vendor.

1. PROJECT OVERVIEW

1.1 Introduction

The Minnesota Department of Transportation (Mn/DOT), with technical guidance from the project's Technical Advisory Committee (TAC) and Federal Highway Administration (FHWA), is conducting a continuation of the pooled fund "Evaluation of Non-Intrusive Technologies for Traffic Detection" (NIT) Project. The goals of this phase (TPF-5[171]) are to conduct focused field tests of non-intrusive technologies and explore the deployment issues and costs associated with the technologies. The project is examining the traffic data collection capabilities of each sensor, including collection of volume, speed and length-based and axle-based classification data.

Sensors were evaluated in a variety of traffic and environmental conditions at a freeway test site. Emphasis was placed on urban traffic conditions, such as heavy congestion, and varying weather and lighting conditions. Standardized testing criteria were developed so that the results from this project will be directly comparable to results obtained by other transportation agencies. The Twin Cities Metropolitan Area provides an excellent opportunity to evaluate the sensors in many types of weather extremes, including varying temperatures, rain, snow and high winds. As with previous phases, the primary test location is the NIT Test Site on I-394 at Penn Avenue, near downtown Minneapolis, Minnesota.

Based on direction from the project's TAC, traffic detection sensors representing the following four non-intrusive technology groups were evaluated.

1. Active infrared/laser
2. Magnetic
3. Radar
4. Video

1.2 Background

Monitoring traffic volumes has been a basic element of highway program administration for over seven decades. The collection of historical traffic volume data is used for a variety of purposes, such as historical trend analysis and forecasting to plan for future investments. Traffic volume measurements are also valuable indicators of congestion, exposure rates, potential air pollutant concentrations, expected fuel tax collections and as a general measure of economic conditions. The collection of other traffic parameters, such as speed and vehicle classification, is increasingly important as pavement design models become more sophisticated and new types of sensors are used for highway operations.

Non-intrusive technologies have a long history of use in transportation applications. Magnetic sensors were used as early as the 1940s. By the 1960s, ultrasonic and microwave sensors were also on the market. However, by the end of the 1960s, inductive loops and pneumatic road tubes became the dominant detection methods and largely replaced non-intrusive methods.

From the early 1960s to the early 1990s, travel on the nation's highways increased from 46 percent to 60 percent. Despite the demanding nature of data collection in urban areas, the urbanization of the nation's highway travel, congestion concerns, air pollution and intermodal coordination make it imperative that thorough traffic monitoring is done on these urban facilities. Major impediments to urban area traffic monitoring are cost, safety and traffic disruption associated with the installation of intrusive detectors in active roadways.

This project has continued the work begun in the previous phases, completed in 1997 and 2002. These phases featured field tests at both freeway and intersection sites. A combined total of 26 sensors representing eight different technologies were evaluated in varying traffic and environmental conditions. The evaluations involved volume, speed, occupancy, presence and classification data with some vehicle classification. Results were compared to conventional roadway-based sensor technologies. In addition, a pooled fund study completed in 2005 studied non-intrusive sensors used in a temporary application. For more information, refer to the NIT Phase I, NIT Phase II and PNITDS Final Reports at Mn/DOT's Minnesota Guidestar Web site at http://www.dot.state.mn.us/guidestar.

New technologies and sensors continue to emerge as manufacturers respond to the expanding needs of traffic data collectors. It is imperative to continuously review the new developments and search for potentially more efficient alternatives to the commonly used road tube, inductive loop and piezo data collection methods. This pooled fund project provides a cost-effective platform for continuing this important research and subsequent dissemination of findings.

1.3 Role of Non-Intrusive Technologies

Comprehensive historical data provides the basis for many of the decisions made regarding the transportation infrastructure. The traditional methods of urban traffic data collection are used at both fixed locations and temporary locations. Typically, inductive loops require cuts into the pavement and are typically used at fixed location counting stations. Road tube counters and manual counts are typically used at temporary locations where only a short period of data collection is needed. Inductive loops serve many of the detection requirements of traffic operations and ITS applications while both loops and axle sensors (such as piezos and road tubes) are used to gather historical data. Non-intrusive technologies can play an important role in providing the detection requirements for both historical and real-time applications.

Traditional data collection methods can present difficulties and limitations in urban areas. These difficulties include the following:

- All intrusive technologies have safety implications. For example, on very congested freeways and arterials, volumes may be high at all times, not providing a window for safe installation. Personnel safety is also a concern when road tubes must be set where traffic volumes are high. Field personnel conducting manual counts risk exposure to vehicular traffic during counts. Also, installing intrusive technologies on moderate- or high-volume roadways can result in traffic disruptions, unless done during new construction or when the roadway will be closed for other reasons such as resurfacing. Temporary closure of traffic lanes is sometimes needed to provide safety for personnel installing road tubes, inductive loop detectors, or any other in-road sensor.

- Cost limits the amount of locations where fixed counting stations can be installed. Many agencies do not have sufficient resources to install enough fixed counting stations in urban areas to provide for all of their traffic detection needs.

- Roadway geometrics can make it difficult to obtain accurate counts using intrusive technologies, including geometries where there is significant lane changing or where vehicles do not follow a set path in making turns. Arterial geometrics with multi-lane roads are difficult to count with road tubes because they must be laid across many lanes. Road tubes are also difficult to use on roads with curbs and/or gutters. Weaving sections are also a problem because vehicles may be double-counted or missed altogether. This is particularly problematic in urban areas.

- Environmental conditions, such as rain or snow, cause wet pavement that inhibits the use of road tubes. Also, any sensor that is placed on the pavement, such as magnetometers, piezos, or road tubes, is susceptible to being damaged by snow removal equipment or other street maintenance equipment. The traditional intrusive road tube methods are also a problem in these extreme conditions. Low temperatures also hamper tube and weigh-in-motion accuracy and shorten battery life.

- Congested or stop-and-go traffic can lead to poor data collection. Some technologies detect stationary vehicles, even if they do not move for several minutes. Short headways can lead to miscounting and misclassification.

- Collecting data through direct observations by field personnel has a number of drawbacks, including cost, lighting conditions and staffing limitations. Limited vantage points can also cause difficulties for manual counts. Some valuable traffic data is not collected, because it is impractical using traditional methods.

Despite these issues, inductive loop detectors have the advantage of being accurate when operating correctly. This is largely due to the fact that the technology has matured through being in use for several decades. Also, transportation professionals are very familiar with the operational and maintenance needs of loops and other conventional data collection methods.

1.4 Definition of Non-Intrusive Technologies

Non-intrusive technologies, as defined for the purposes of this test, are traffic detection sensors that cause minimal disruption to normal traffic operations during installation, operation and maintenance compared to conventional detection methods. They can also be deployed more safely than conventional detection methods. Based on this definition, non-intrusive sensors refer to those sensors that do not need to be installed in or on the pavement, but can be mounted to the side of the roadway or above the roadway. In addition, sensors that are installed beneath the pavement by “pushing” a conduit under the roadway are considered non-intrusive.

A further definition of non-intrusive technologies developed for this phase of testing excludes overhead-mounted sensors because of the challenges in installing and maintaining devices in this location. In addition, the sensor systems must be able to monitor multiple lanes. These requirements reflect the challenges in an urban environment. Refer to section 1.8.1 for the full sensor selection criteria. The technologies identified for evaluation include active infrared (laser), magnetic, radar and video detection sensors.

1.5 Description of Non-Intrusive Technologies

A brief overview of the principles, stated capabilities, and limitations of four technologies are described below. Other sources provide a more thorough description of each technology. Interested readers are encouraged to consult the *Traffic Detector Handbook* by the FHWA and JHK & Associates, the *Detection Technology for IVHS* by the FHWA and Hughes Aircraft Company, *Sensor Technologies and Data Requirements for ITS* by Dr. L. A. Klein, or *A Summary of Vehicle Detection and Surveillance Technologies used in Intelligent Transportation Systems*, produced by The Vehicle Detector Clearinghouse.

Active Infrared/Laser

Basic Principles of Operation

Infrared sensors detect infrared radiation (electromagnetic radiation with a frequency range of 10^{11} to 10^{14} Hertz) that reaches the detector. Active infrared sensors transmit low-energy laser beam(s) to a target area on the pavement and measure the time for the reflected signal to return to the sensor. The presence of a vehicle is measured by the corresponding reduction in time for the signal return.

Infrared detectors work well in both day and night conditions. They are not affected by sun glare, headlight glare, or elongated shadows.

Stated Capabilities

Depending on the particular sensor and how it is deployed, active infrared sensors can detect volume, presence, length, speed and the number of axles.

Limitations

Active near-infrared sensors are limited by occlusion as well as dirt and road-grime on the lens. These sensors are also generally limited to the same range in inclement weather as can be seen with the human eye.

Magnetic

Basic Principles of Operation

Magnetometers are passive sensors that detect perturbations in the Earth's magnetic field caused by the metallic components of vehicles. There are two major types of magnetometers: induction magnetometers and dual-axis magnetometers. Induction magnetometers, sometimes referred to simply as magnetic detectors, measure changes in the magnetic flux lines when metal components in a vehicle, especially the engine, travel past the detection zone. Other components of a vehicle, such as the alternator, also create changes in the magnetic field. The magnetic flux change can be observed by measuring the corresponding changes in the electric current induced in the sensor. These current fluctuations give an imprint of the vehicle's presence, but cannot detect stopped vehicles. Dual-axis fluxgate magnetometers detect changes in the horizontal and vertical components of the Earth's magnetic field caused by the passage or presence of a vehicle. This type of sensor can detect both moving and stationary vehicles.

Stated Capabilities

Magnetic sensors can detect volume, classification, headway, presence and speed with algorithms or two sensors in a speed trap configuration.

Limitations

Unless installed during new construction, sensors that mount beneath the pavement require directional conduit boring for sensor installation. Some induction magnetometers cannot detect stopped vehicles.

Radar

Basic Principles of Operation

Radar sensors use a continuous, frequency-modulated or phase-modulated signal to determine the time delay of the return signal, thereby calculating the distance to the detected vehicle. Radar sensors have the additional ability to sense the presence of stationary vehicles and to sense multiple zones through their range finding ability.

Stated Capabilities

Radar sensors can detect volume, presence, classification, speed and headway.

Limitations

Radar sensors can experience dead detection zones and "ghost" vehicles when installed in areas with barriers, fencing, or other obstructions.

Video

Basic Principles of Operation

Video-based detectors use a microprocessor to analyze the video image input. Different approaches are used by video detection sensors. Some analyze the video image of a target area on the pavement. The change in the image of the target area as a vehicle passes through the target area is processed. Another approach identifies when a target vehicle enters the video field of view and tracks the target vehicle through this field of view. Still other video sensors use a combination of these two approaches.

Stated Capabilities

Videos sensors can be used to collect volume, speed, presence, occupancy, density, queue length, dwell time, headway, turning movements, acceleration, lane changes and classification.

Limitations

Environmental conditions that affect the video image quality can reduce system performance. Such conditions include fog, rain, dust or snow in the air; frost, condensation or dirt on the camera lens; and adverse lighting conditions, such as headlight glare on wet pavement, low-angle sunlight, poor vehicle-road contrast, and headlight reflection on curved roadways. Proper setup and calibration is critical to gathering accurate data and achieving satisfactory performance in poor lighting conditions.

1.6 Project Team Description

The project was managed by a core group of project team members. They include the following individuals:

- Jerry Kotzenmacher, Mn/DOT – Mn/DOT Project Manager
- Steven Jessberger, FHWA – Project Liaison
- Erik Minge, SRF Consulting Group, Inc. – SRF Project Manager
- Scott Petersen, SRF Consulting Group, Inc. – Project Team Member

The project was guided by participating state agencies that are part of this pooled initiative. These individuals comprise the TAC:

Connecticut	Anne-Marie McDonnell
Florida	Richard Reel
Georgia	Scott Knight
Hawaii	Goro Sulijoadikusumo
Idaho	Jack Helton
Illinois	Rob Robinson

Iowa	Troy Jerman
New York	Kurt Matias
Minnesota	Jerry Kotzenmacher
Mississippi	Mike Stokes
Montana	Tedd Little
Ohio	Lindsey Pflum
Texas	Robert Wheeler
Wisconsin	Susie Forde

The project team would also like to thank the vendors who donated their time and equipment (see Section 8.3.1).

1.7 Project Audience

One of the project goals is to make the NIT evaluation results a valuable source of information to a variety of transportation professionals. Emphasis is placed on those individuals responsible for routine traffic data collection. To this end, the test results are presented in a readily accessible format and include extensive discussion of the installation and maintenance requirements of each detector. The following project audiences have been identified:

- Data collection practitioners
- Traffic operations practitioners
- Professional organizations
- Transportation agencies
- Transportation researchers

1.8 Vendor Participation and Sensors

1.8.1 Selection Criteria

An extensive list of vendors that manufacture non-intrusive sensors was compiled and reviewed by the project management team and TAC. The following criteria were used to determine which sensors should be considered for the NIT project:

1. The sensor must cause either no disruption or very minimal disruption to normal traffic operations during installation. The sensor must be sidefire or mounted beneath without cutting into the pavement.

2. The sensor must be available in final form and must have been successfully field tested by either the vendor or an independent agency.

3. The manufacturer/vendor must be willing to provide technical support for the sensor during installation as well as during the initial test period. Setup must be reasonably simple.

4. The sensor must have outputs that are reasonably compatible with existing data collection programs and sensors. Outputs should be capable of being loaded into a database without significant manual manipulation or manual data input.

5. The sensor must have a production and total deployment cost that is cost-effective compared to traditional systems.

6. The sensor must have the ability to provide data pertaining to key requirements of this project, such as vehicle classification, multiple lane detection, and either sidefire or under pavement mounting.

1.8.2 Benefits of Participation

There is a tendency for some of the vendors to be skeptical of "yet another test program" because they feel there have been enough tests of their sensors. The vendors of commercially available sensors generally indicated that they would like to see a more rapid incorporation of these sensors into use, rather than continued testing programs. For this reason, the following distinction between this test and the other evaluations was emphasized:

- This test will use several techniques to gather extensive baseline data against which the performance of the sensors will be compared, providing a permanent record of the sensor and baseline data to the vendors.

- Each vendor will be provided with the output from their sensor and output from the baseline data. In addition, a video record of the roadway target area will be available upon request.

- The test will provide a long-term test bed for vendors to evaluate their products in a wide variety of environmental and traffic conditions. It was made clear to each vendor that every effort will be made to provide them with valuable data on a timely basis in return for their participation in the test.

- The test will focus on evaluating of the capabilities of the various sensors and will evaluate the relative cost effectiveness of the sensors for the appropriate types of traffic data collection efforts.

Vendors participating in the NIT project will realize two primary benefits:

- Participating in the evaluation will yield valuable information on sensor performance in a variety of real-world weather, mounting, and traffic conditions. Vendors participating in the previous phases found this information useful in product development efforts.

- Evaluation results will be widely distributed to transportation practitioners via the project's Web site.

1.8.3 Vendor Selection

Based on the selection criteria noted earlier, the TAC identified six vendors that they would like to see participate in the NIT project. These vendors were contacted in May 2009 and invited to join the study. One of the vendors, ISS Canada (manufacturer of the RTMS), declined participation. Table 1 lists the five vendors that agreed to participate. The text that follows provides a brief description of the sensors and their features.

Table 1. Summary of Participating Vendors and Sensors

Technology	Vendor	Sensor
Radar	Wavetronix, LLC.	SmartSensor HD (Model 125)
Magnetic	Global Traffic Technologies (GTT)	Canoga Microloop
Active Infrared (Laser)	Control Specialists Company	TIRTL
Active Infrared (Laser)	PEEK Traffic	AxleLight
Video	Miovision Technologies, Inc.	Video Collection Unit

<u>Wavetronix SmartSensor HD</u>

The Wavetronix SmartSensor HD is a radar sensor. The SmartSensor HD can detect up to 10 lanes of traffic and has a detection range of 250 feet and has the ability to measures traffic volume, individual vehicle speed, average speed, 85th percentile peed, vehicle classification by length, average headway, average gap, lane occupancy, and presence through the RS 232 or RS 422 communication module. It requires an 8 to 28 V DC power supply.

<u>GTT Canoga Microloops</u>

The GTT Canoga Microloops are magnetic sensors that are installed under the roadway in conduit bored from the roadway shoulder. They perform similarly to loops and can report volume, speed (when installed in a speed trap) and vehicle length. The vehicle length can be binned into length-based classes. Note that although these sensors do not individually provide multi-lane detection, they can provide multilane detection as part of a larger system including multiple sensors.

<u>PEEK AxleLight</u>

The AxleLight is a laser sensor manufactured by Peek Traffic. The AxleLight emits a near infrared pulsed beam which is detected by the sensor when it bounces off of vehicle wheels. The AxleLight is capable of detecting traffic in up to four lanes. Two AxleLight sensors mounted on one side of the road were used in this study to collect volume, speed, and axle-based classification data. Both sensors were attached to a PEEK ADR 1000 which stores traffic data.

Transportable Infra-Red Traffic Logger (TIRTL)

The TIRTL is a sidefire infrared light detection sensor that must be installed on each side of a subject roadway. It has a transmitter unit and a received unit. The receiver unit stores data and is used for sensor configuration. Both sensors must be installed perpendicular to the roadway and pointed at one another. The system has a variety of communications methods that can be installed onboard the sensor, although this test used the RS-232 communications.

Miovision

The Miovision is a video sensor that records data on a video controller unit that stores recorded video (VCU). The Miovision system includes a telescoping mast that can be attached to an existing pole or can be mounted as part of a standalone tripod system. The video must be uploaded to Miovision for processing at a cost per hour of data processing.

1.9 National Standards

Emphasis has been placed on producing traffic and transportation hardware that is transferable among competing vendors. This means that a given hardware component is not dependant on a manufacturer's proprietary protocol.

ASTM The American Society of Testing Materials (ASTM) has developed standard test methodologies for evaluating traffic sensors. The ASTM subcommittee E17.52 has prepared this methodology. While this effort only addresses conventional vehicle data collection methods (road tubes, piezoelectric devices, inductive loop detectors, and tape switches), the results will also be applicable to non-intrusive technologies. The ASTM initiative includes procedures for field and bench testing, desired sensor performance standards, and methods for documenting test results. ASTM has prepared the *Draft Standard Test Method for Validating Vehicle Data Collection Devices for Vehicle Counts and Classifications* and *Standard Specification for Highway Traffic Monitoring Devices.* For more information refer to www.astm.org.

The following documents were used indirectly to inform the evaluation:

- FHWA Traffic Monitoring Guide (2001)
- FHWA Traffic Detector Handbook (2006)
- HPMS Field Manual (2005)

2. FIELD TEST DESCRIPTION

Each sensor was tested for its ability to accurately detect and classify vehicles under a variety of traffic and weather conditions. This section describes the testing hardware and software, baseline, sensors and tests conducted for the project.

2.1 Test Site Description

The NIT test site is located at I-394 and Penn Avenue in Minneapolis Minnesota and is the same location used in Phases I and II. This site includes freeway and intersection roadway traffic, and bicycle and pedestrian trails. Minnesota weather conditions provide a suite of weather extremes, including high winds, rain, fog, sleet, snow and a wide variety of temperature conditions. The NIT Test Site offers a significant range of traffic conditions, such as recurring congestion in both the morning and afternoon peak periods and lower volumes with free-flow conditions in the evening and on weekends. The site also offers a variety of lighting conditions, depending on the time of year. Low-angle sunlight creates long shadows in the winter and bridge shadows are a factor year-round. All of these conditions create a challenging test environment.

The NIT Test Site is equipped with dual loop detectors in each of the three eastbound lanes of I-394 (one of which was used in the PLP array). Six 11-foot piezoelectric sensors were installed at the beginning of this project to provide an accurate axle-based classification baseline, providing a piezo-loop-piezo configuration. Photographs of the test sites are provided in Figures 1 to 4.

The freeway test site features a variety of side mounting locations. The active infrared devices were mounted on a guard rail on a base as recommended by the manufacturer. All other devices were mounted on sidefire poles or railings. Mounting heights ranged from 10 to 40 feet. One pole is approximately 19 feet from the edge of the closest travelled lane. Another pole was installed 30 feet from the nearest travelled lane.

In addition, testing was conducted at Mn/DOT’s TH 52 weigh-in-motion (WIM) station to obtain long term data from sensors that could not be installed in long term deployments at the NIT Test Site, such as the TIRTL. This site features significant truck traffic and already had a Piezo-Loop-Piezo (PLP) baseline. The roadway at this site is shown in Figure 4.

Figure 1. NIT Test Site

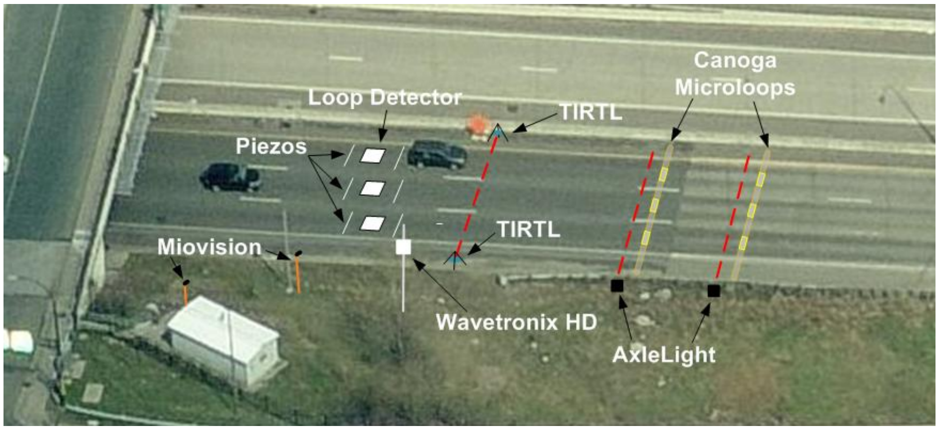


Figure 2. NIT Test Site Showing Approximate Sensor Locations

Figure 3. NIT Test Site Showing Three Eastbound I-394 Test Lanes

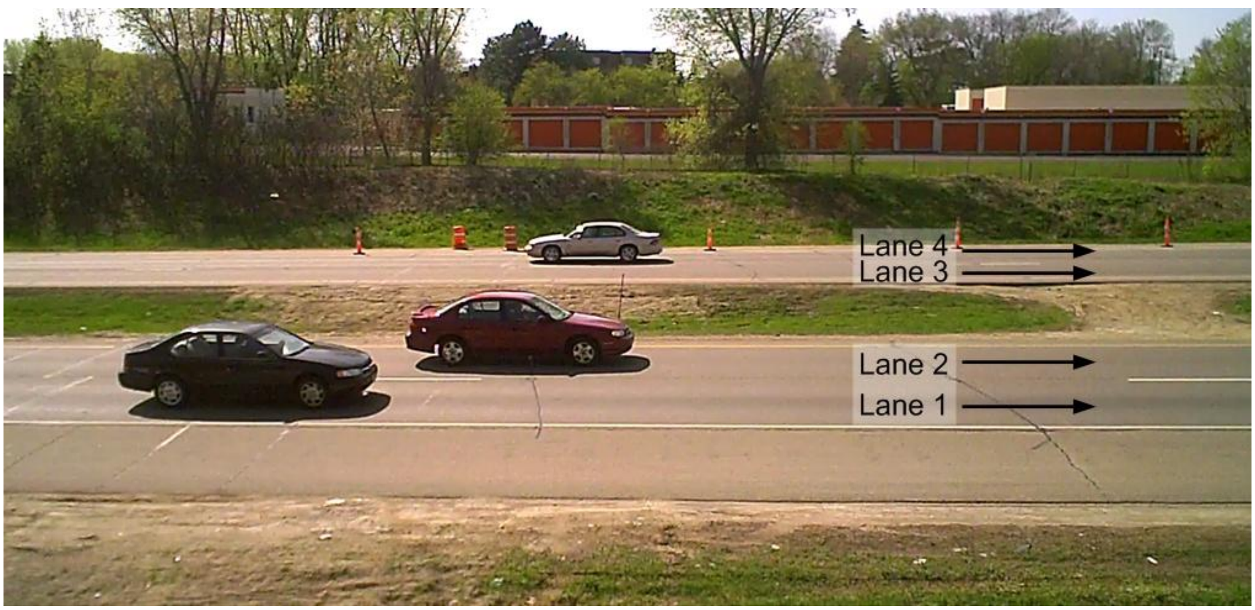


Figure 4. TH 52 Test Site

2.2 Data Acquisition System

The data acquisition system consists of both hardware and software components that capture per-vehicle records (PVR). The hardware components include the following:

- Personal computers: used for sensor calibration, video recording, data downloading, data storage and data processing
- Video camera and USB video capture device (for overhead camera)
- High-definition video camera (for sidefire video)
- Equipment rack: used to hold data acquisition components AC power supplies, loop detector cards and the traffic recorder.
- PEEK ADR 3000: used to process piezo-loop-piezo (PLP) detections. It allowed for the collection of all data outputs simultaneously. The ADR was programmed to collect the data from detectors and baseline loops in 15-minute intervals.

2.3 Baseline Description and Ground-Truthing

2.3.1 Baseline Sensor Data

Four primary data types were addressed in this evaluation: volume, speed, length-based classification and axle-based classification. Each of these data types requires a different baseline procedure. Table 2 presents these parameters and their proposed baselines. These traffic parameters were selected in consultation with the project's TAC.

Table 2. Traffic Parameters

Traffic Parameter	Baseline Data Source
Volume	PLP with manual checking
Speed	PLP
Classification by Length	Video
Classification by Axles	PLP

2.3.2 Piezo-Loop-Piezo Baseline

At the NIT Test Site, the PLP baseline was recommended by the TAC because it is widely accepted as an accurate method for obtaining axle spacing. For this project, the PLP baseline was set up to provide accurate per-vehicle speed and axle-based classification. Vehicle acceleration or deceleration can cause errors in speed detection, but these errors are mitigated to some extent because the piezos are spaced only ten feet apart. The axle-based classification scheme was developed from the LTPP Classification scheme, with classes added to capture additional vehicles. The LTPP scheme relies on also having WIM capabilities, which this project's test site does not have, so adjustments were necessary where there were overlapping classes. The six adjusted classes are highlighted in Table 3.

Table 3. Modified LTPP Classification Scheme for NIT Phase 3
Modified From March 2006 Version of LTPP Classification Scheme

Class	Vehicle Type	No. Axles	Bin	Spacing 1	Spacing 2	Spacing 3	Spacing 4	Spacing 5	Spacing 6	Spacing 7	Spacing 8
1	Motorcycle	2	1	1.0 - 5.9							
2	Passenger Car	2	2	6.0 - 10.1							
3	Other (Pickup/Van)	2	3	10.2 - 13.0							
4	Bus	2	4	23.1 - 40.0							
5	2D Single Unit	2	5	13.1 - 23.0							
2	Car w/ 1 Axle Trailer	3	6	6.0 - 10.1	6.0 - 25.0						
3	Other w/ 1-Axle Trailer	3	7	10.2 - 23.0	6.0 - 25.0						
4	Bus	3	8	23.1 - 40.0	3.0 - 7.0						
5	2D w/ 1-Axle Trailer	3	9	6.0 - 23.0	6.3 - 30.0						
6	3-Axle Single Unit	3	10	6.0 - 23.0	2.5 - 6.2						
8	Semi, 2S1	3	11	6.0 - 23.0	11.0 - 45.0						
2	Car w/ 2-Axle Trailer	4	12	6.0 - 10.1	6.0 - 30.0	1.0 - 11.9					
3	Other w/ 2-Axle Trailer	4	13	10.2 - 13.0	6.0 - 30.0	1.0 - 11.9					
5	2D w/ 2-Axle Trailer	4	14	13.1 - 26.0	6.3 - 40.0	1.0 - 20.0					
7	4-Axle Single Unit	4	15	6.0 - 23.0	2.5 - 6.2	2.5 - 12.9					
8	Semi, 3S1	4	16	6.0 - 26.0	2.5 - 6.2	13.0 - 50.0					
8	Semi, 2S2	4	17	6.0 - 26.0	8.0 - 45.0	2.5 - 20.0					
3	Other w/ 3-Axle Trailer	5	18	10.2 - 23.0	6.0 - 25.0	1.0 - 11.9	1.0 - 11.9				
5	2D w/ 3-Axle Trailer	5	19	6.0 - 23.0	6.3 - 35.0	1.0 - 25.0	1.0 - 11.9				
7	5-Axle Single Unit	5	20	6.0 - 23.0	2.5 - 6.2	2.5 - 6.2	2.5 - 6.3				
9	Semi, 3S2	5	21	6.0 - 30.0	2.5 - 6.2	6.3 - 65.0	2.5 - 11.9				
9	Truck+FullTrailer (3 - 2)	5	22	6.0 - 30.0	2.5 - 6.2	6.3 - 50.0	12.0 - 27.0				
9	Semi, 2S3	5	23	6.0 - 30.0	16.0 - 45.0	2.5 - 6.3	2.5 - 6.3				
11	Semi+FullTrailer, 2S12	5	24	6.0 - 30.0	11.0 - 26.0	6.0 - 20.0	11.0 - 26.0				
10	Semi, 3S3	6	25	6.0 - 26.0	2.5 - 6.3	6.1 - 50.0	2.5 - 11.9	2.5 - 10.9			
12	Semi+Full Trailer, 3S12	6	26	6.0 - 26.0	2.5 - 6.3	11.0 - 26.0	6.0 - 24.0	11.0 - 26.0			
7	6 Axle, Single-Unit Trucks	6	27	6.1 - 23.0	1.0 - 6.0	1.0 - 6.0	1.0 - 6.0	1.0 - 13.0			
7	7 Axle, Single-Unit Trucks	7	28	6.1 - 23.0	1.0 - 6.0	1.0 - 6.0	1.0 - 6.0	1.0 - 6.0	1.0 - 6.0		
10	7 Axle, Single Trailer Trucks	7	29	6.1 - 23.0	1.0 - 6.0	6.1 - 30.0	1.0 - 6.0	1.0 - 6.0	1.0 - 6.0		
13	7 Axle Multi-Unit Trucks	7	30	6.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0		
13	8 Axle Multi-Unit Trucks	8	31	6.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	
13	9 Axle Multi-Unit Trucks	9	32	6.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0	3.0 - 45.0

Spacings in feet
Modifications to the March 2006 LTPP scheme are highlighted in gray

The NIT Test Site's PLP baseline was ground-truthed by driving three vehicles of known axle spacing and length through each of the three lanes. The baseline was accurate to within 1 to 2 mph for speed and 0.1 to 0.2 feet for axle spacing in each of three runs on all three vehicles. The average error when compared to the physical length of the vehicles is shown in Table 4. Note that one tenth of a foot readings are as precise as the test site's PEEK ADR 3000 (ADR) data classifier will report.

Table 4. NIT Test Site Baseline (PLP) Axle Spacing Accuracy

Vehicle Type	Probe Vehicle Axle Spacing (ft)	Average PLP Axle Spacing, three runs (ft)	PLP Percent Error
Class 2 Car	8.1	8.2	1.2%
Class 5 Truck	15.5	15.7	1.3%
Class 9 Truck	17.5	17.6	0.6%
Class 9 Truck	4.3	4.4	2.3%
Class 9 Truck	32.2	32.4	0.6%
Class 9 Truck	4	4.1	2.5%
Average Error			**1.4%**

The baseline count was ground-truthed and was generally accurate, but vehicle lane changes caused double counting, accounting for most of the approximately two percent error. As explained below, double counted vehicles were removed from the baseline data set with the video baseline review. In general, the PLP baseline can capture vehicles at speeds down to about 10 mph. At the NIT Test Site, errors developed at speeds less than 10 mph (i.e. stop-and-go conditions) because the system had trouble identifying how the piezo hits map between the end of the first vehicle and the beginning of the next one. At such slow speeds, manual counting and classification was sometimes performed to provide a more accurate baseline.

At the TH 52 test site, Mn/DOT had recently conducted a calibration of their WIM station and found that their PLP sensors were within 0 to 1.5 percent error for axle spacing distances. This site does not typically experience traffic speeds below 10 mph. This site has an IRD iSinc WIM system. Mn/DOT's calibration tests were taken to the nearest hundredth of a foot as shown in Table 5.

Table 5. TH 52 Test Site Baseline (PLP) Axle Spacing Accuracy

	Probe Vehicle Length (ft)	Lane 1 PLP Length (ft)	Lane 2 PLP Length (ft)	Lane 3 PLP Length (ft)	Lane 4 PLP Length (ft)
Axle Spacing 1	13.81	13.72	13.67	13.76	13.67
Axle Spacing 2	4.23	4.21	4.19	4.21	4.19
Axle Spacing 3	25.07	25.41	25.36	25.34	25.36
Axle Spacing 4	3.94	3.91	3.96	3.95	3.96

	Percent Error				
Lane		**Lane 1**	**Lane 2**	**Lane 3**	**Lane 4**
Axle Spacing 1		-0.7%	-0.3%	0.7%	-0.7%
Axle Spacing 2		-0.6%	-0.3%	0.5%	-0.5%
Axle Spacing 3		1.4%	-0.2%	-0.1%	0.1%
Axle Spacing 4		-0.7%	1.3%	-0.4%	0.4%

2.3.3 Video Baseline

A high-definition (720p) video camera was used to record video from the NIT shelter window that overlooks the test lanes. The video camera was oriented so that it views the PLP baseline directly and is perpendicular to the PLP sensors. The video was reviewed after data collection for comparison against the sensor and other baseline data sources. One issue with this type of baseline is that occlusion can cause vehicles to be missed. This has not been a major issue except in severely congested traffic. In most other cases, it is possible to see partially occluded vehicles behind a large truck or see vehicles as they enter or leave the test area. A separate video camera was mounted above the test lanes on an overhead gantry to view vehicles when occlusion issues occurred.

The baseline was also used to measure vehicle length with video screenshots. Paint marks were made 50 feet apart on the inside shoulder and 30 feet apart on the outside shoulder (nearest the camera) at the NIT Test Site. These marks were used to calibrate screenshots to determine vehicle length. An adjustment factor was applied to each lane because of the camera's perspective. It was found that it is important to measure the vehicle when it is in the center of the video area to limit errors due to skewed viewing angles.

A simple analysis was conducted to validate the video measurement process by comparing the video measurements to the ground-truthed PLP baseline. The data presented in Figure 5 shows that across the range of axle spacings, most axle spacing measurements were within three percent error. Table 6 shows more detail about this finding.

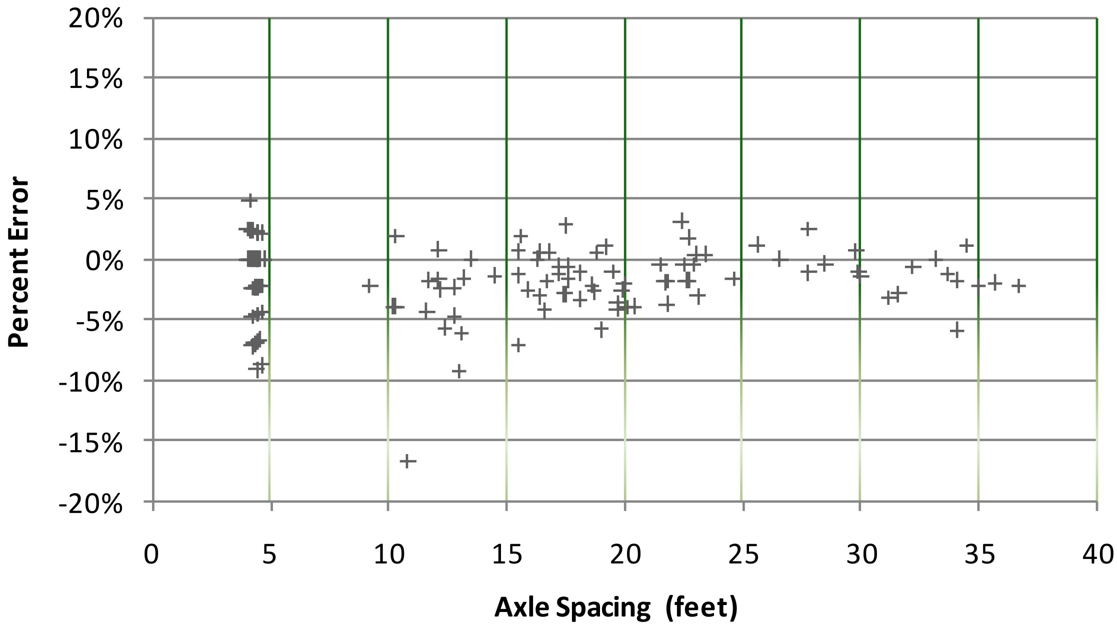


Figure 5. Percent Error of Various Axle Spacings: Video Compared to PLP Baseline

Table 6. Results of Video-Axle Spacing Comparison

Axle Spacing (feet)	Number of Samples	Average Percent Error	Absolute Average Percent Error
0-10	50	-1.6%	2.7%
10-20	46	-2.4%	2.9%
20-30	24	-0.8%	1.6%
30-40	12	-1.8%	2.0%

2.4 Traffic Data Parameters

Volume

Piezos and loop detectors were used to provide the baseline data for traffic volume. Piezos emit an electronic charge and loop detectors sense a change in inductance when a vehicle passes over them. Each time the vehicle passes the sensor, a count is added to the total volume. The data collection system captures per-vehicle records which can be compared to the sensor data.

Speed

Speed outputs obtained from the PLP baseline provided an accurate baseline measure of vehicle speeds because the PLP baseline is in a speed trap configuration. PVR speed records were collected.

Axle-Based Classification

Axle-based classification is determined based on both the number of axles per vehicle and the inter-axle spacing of those axles. FHWA has defined 13 vehicle classes based on axle configurations, see Table 7. This vehicle classification scheme was generally followed and was used for analysis in this evaluation.

Data from the piezoelectric sensors and loop detectors was sent to an automated traffic classifier to give per-vehicle axle-based classification. The final result is an accurate baseline to measure the distance between each set of axles for each vehicle.

Table 7. FHWA 13 Class Axle-Based Classification Scheme

Class Bin	No. of Axles	Vehicle Description
1	2	Motorcycles
2	2	Passenger Vehicles
3	2	Other 2-axle, four tire single unit vehicles
4	2 or more	Buses
5	2	2-Axle, 6-Tire, Single Unit Trucks
6	3	3-Axle Single Unit Trucks
7	4 or more	4 or more Axle Single Unit Trucks
8	3,4	4 or fewer Axle Single-Trailer Trucks
9	5	5-Axle Single-Trailer Trucks
10	6 or more	6 or more Axle Single-Trailer Trucks
11	4,5	5 or fewer Axle Multi-Trailer Trucks
12	6	6-Axle Multi-Trailer Trucks
13	7 or more	7 or more Axle Twin Trailer Semi Trucks

Length-Based Classification

Although axle-based classification systems are used by many agencies, the FHWA does not require exclusive use of this type of classification. Some states are moving towards length-based detection. Because there is not yet a standard method to classify vehicles by length, a number of different agencies have recommended schemes. It is common to aggregate data into three to five length-based bins. The proposed length-based classification scheme is in Table 8. The table also maps the length bins to FHWA classes. These bins were determined based on a survey of multiple states and a 2005 Mn/DOT study that recommended the use of these bins. A per-vehicle analysis of length will be done for each sensor which can then be aggregated into any set of length-based bins.

Table 8. Vehicle Length-Based Classifications

Vehicle Class	Vehicle Length	Vehicle Class
Motorcycle	0 to 7ft	1
Passenger Vehicles (PV)	7 to 22 ft	2, 3
Single Unit Truck (SU)	22 to 37 ft	4-7
Combination Trucks (MU)	Over 37 ft	8-13

2.5 Goal 1: Assess the Performance of Non-Intrusive Technologies

The primary goal of the NIT project is to compare non-intrusive vehicle detection technologies to conventional roadway-based vehicle detection technologies. Each sensor was tested for its ability to accurately collect volume, speed and length- and axle-based classification data. Each of these parameters was tested in various traffic and weather conditions, as listed below.

Objective 1-1: Assess Performance in Various Traffic Conditions

Tests were conducted in varying levels of traffic congestion to see if they affect sensor performance. Congestion was expressed as the conventional "Level of Service" rating as defined in Table 9. For this project, congestion was tracked as either LOS A-D, LOS E or LOS F.

Table 9. Level of Service Definitions

LOS	Definition
A	Free flow conditions exist and vehicles are free to travel at desired speeds. The average spacing between vehicles is 26 car lengths. Density is less than 10 passenger cars per mile per lane (pcpmpl).
B	Free-flow speeds are sustained and the average spacing between vehicles is 17 car lengths. The maximum density is 16 pcpmpl. .
C	Speeds may near the free flow speed. Maneuverability is restricted. Average spacing between vehicles is 11 car lengths and the maximum density is 24 pcpmpl
D	Speeds slightly decline and freedom to maneuver is increasingly limited. Average spacing between vehicles is 8 car lengths and the maximum density is 32 pcpmpl. Any incident may result in queuing.
E	There is little to no room to maneuver at speeds greater than 49 mph. Average spacing between vehicles is 6 car lengths and the maximum density is 45 pcpmpl, which is the freeway capacity limit. Any incident will result in extensive queuing.
F	Traffic operation is under breakdown conditions and queues exist, resulting in reductions in capacity. Demand is greater than capacity.

(Garber and Hoel, 1999).

Objective 1-2: Assess Performance in Various Weather/Lighting Conditions

A variety of environmental variables can affect the accuracy of non-intrusive technologies. The various test conditions are listed below. For each of these scenarios, the full suite of volume, speed and classification tests were performed in rain, snow, low light, shadows, nighttime, wind and extreme temperatures.

2.6 Goal 2: Document Non-Intrusive Technology Deployment Issues

Issues involving sensor deployment provide important information for potential sensor users. Practical considerations must be given to any proposed test site. This test goal focuses on a detailed documentation of the following types of deployment issues pertaining to each sensor: installation issues, usability and maintenance issues.

2.7 Goal 3: Document Non-Intrusive Technology Costs

Detailed information about sensor cost is useful to the project's audience. Costs to be examined include sensor cost, installation cost, operational cost and maintenance cost.

3. TEST METHODOLOGY

This section presents testing and analysis procedures for evaluating non-intrusive sensors. The information presented in this section is not a step-by-step detailed description of test procedures, but rather a generalized set of testing criteria. The basic approach is to utilize a comparative test between baseline data and sensor data for various traffic parameters. The objective is to ensure that the results obtained in this evaluation can be directly and easily compared to results obtained in other evaluations. Using a standard methodology for testing will aid continuity and ultimately reduce the amount of testing that must be conducted.

3.1 Sensor Calibration

After the sensors were mounted and connected, they were checked for basic function. Each sensor was calibrated before any formal data collection activities began. Most sensors had one or more parameters that must be calibrated based on the specific test environment. Sensor calibration is typically an iterative process. Vendor guidelines were followed and sensor performance was monitored during the calibration process.

The calibration procedures were conducted by on-site project staff with assistance from the vendors. Vendors were encouraged to attend sensor setup. The level of expertise needed to calibrate each sensor was gauged and documented.

3.2 Statistical Data Analysis Methods

Data Types

The following data was collected: volume, speed and classification based on vehicle length and axle configuration.

Scatter Plots

Scatter plots show the relationship between two sets of numbers as one series of x-y coordinates. Each point on a scatter plot represents traffic data for a given sampling interval (i.e., 15 minutes) as measured by the baseline on the horizontal axis and the sensor on the vertical axis. Data points falling on a linear 45-degree line represent perfect agreement between the two compared data sets. This approach provides a straightforward visual representation of variation between each sensor and the baseline data. Figure 6 provides examples of volume scatter plots. The one on the left shows that the sensor correlates closely with the baseline data. The one on the right has some problems with undercounting vehicles.

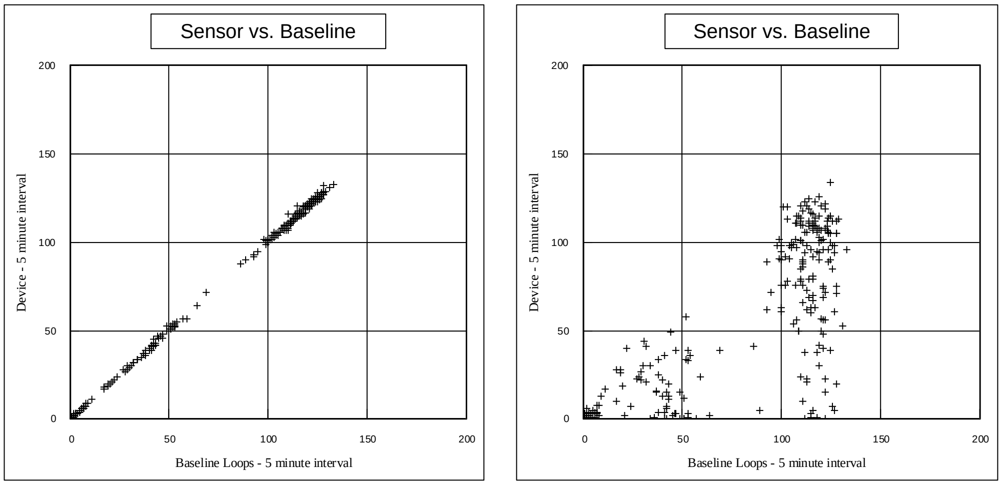


Figure 6. Examples of Volume Scatter Plots

Correlation Coefficient:

The correlation coefficient is a dimensionless index ranging from -1.0 to 1.0 and provides a measure of the sensors' variations from the baseline data from one time interval to the next. A correlation coefficient of 1.0 or -1.0 indicates the data points match the baseline perfectly. A correlation coefficient of 0 indicates data points do not match. The Pearson's product-moment correlation coefficient (r) can be used to calculate the correlation coefficient for each evaluation test. (Milton, 2004).

$$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$$

Percent Difference

Total percent difference is often used to measure sensor performance in collecting volume and speed data. The total percent difference between baseline data and sensor data can be calculated to evaluate sensor performance in a given data collection time period. This information indicates how close the data collected from the sensors are to the baseline data.

Daily total percent differences reveal long-term patterns in sensor performance. However, the aggregation of data into daily totals can obscure the performance of a sensor that both under and over counts with compensating errors. The absolute percent difference (APD) can be used to mitigate these issues. For volume, the absolute percent difference is the ratio of the accumulated absolute errors over the total volume for a complete test period. For speed, the absolute percent difference is the mean of the absolute average speed of each interval. Since absolute errors do not compensate one another, the value is either greater than or equal to the total percent difference. The daily absolute percent difference should be used in conjunction with other statistical measures, such as correlation coefficient.

$$APD = \frac{|Vs - Vm|}{Vm} x100\%$$

Where:
APD = Absolute Percent Difference
Vs = Test parameter from the sensor
Vm = Test parameter from the baseline

Also, tests may be conducted to determine if there are statistically significant differences when comparing data from two different sensors. The analyses are based on comparing the standard error of the mean to the actual differences in the means. The equation for standard error of the mean is given below:

$$s = \sqrt{\left(\frac{s_1^2}{n_1}\right) + \left(\frac{s_2^2}{n_2}\right)}$$

Where:
s_1 and n_1 = standard deviation and sample size for sensor 1
s_2 and n_2 = standard deviation and sample size for sensor 2

Assuming a 95% confidence interval, if the difference between the average APD for two different sensors is greater than 2.131 (t-value with 15 degrees of freedom) times the standard error of the mean, the difference is considered to be statically significant. If the difference is less than 2.131 times the standard error of the mean, it can be concluded that the difference in data could be due to random error. (French Engineering)

Matrix Relationships

A matrix will be used compare the accuracy of a sensor to the baseline. An example of this is shown below in Table 10.

Table 10. Comparison of Manual Classification to ATR Classification

		Manual Length Class			
		1	**2**	**3**	**4**
Sensor Length Class	**4**			2	59
	3		4	10	
	2		2		
	1	-			

4. RESULTS

This section presents the results of the tests, grouped by sensor.

4.1 Wavetronix SmartSensor HD

Wavetronix SmartSensor HD – Volume

Volume results are very consistent over the course of multiple months of data collection and generally were not affected by traffic and weather conditions. However, occlusion was noticed to diminish the accuracy of the sensor in heavily congested conditions. Because the sensor is mounted at a location that does not have line of sight past large trucks, vehicles in the near lane can occlude vehicles in adjacent lanes. The sensor has a 6.5 degree field of view in the horizontal plane and 65 degrees in the vertical plane. Truck volumes as a percentage of general traffic flow are medium to low (about five percent across all lanes), but slow-moving trucks occlude the other lanes for a significant amount of time. For example, a 65-foot truck traveling 10 mph occludes the sensor for approximately 4.4 seconds. Assuming maximum flow rate at level of service E, the truck would occlude the sensor from detecting two to three vehicles in each of the occluded lanes. With similar assumptions, this translates to undercounting of about five percent in the occluded lanes throughout a period of uniform traffic flow. In reality, traffic flow is more stochastic with non-uniform velocities and these errors are avoided more often than a simple model can determine.

Figure 7 illustrates the effect slow traffic in the first lane has on adjacent lane volume accuracy. While Lane 1 volumes are consistently accurate, even when speeds drop, Lane 2 and Lane 3 volumes drop off due to occlusion from Lane 1. From 14:30 to 15:30, the sensor missed 20.0 percent of the vehicles in Lane 2 and 22.6 percent of vehicles in Lane 3. During the same period of slow moving traffic, it only undercounted 12.2 percent of vehicles in Lane 1. During this period, vehicles in Lane 1 were travelling 0-10 miles per hour.

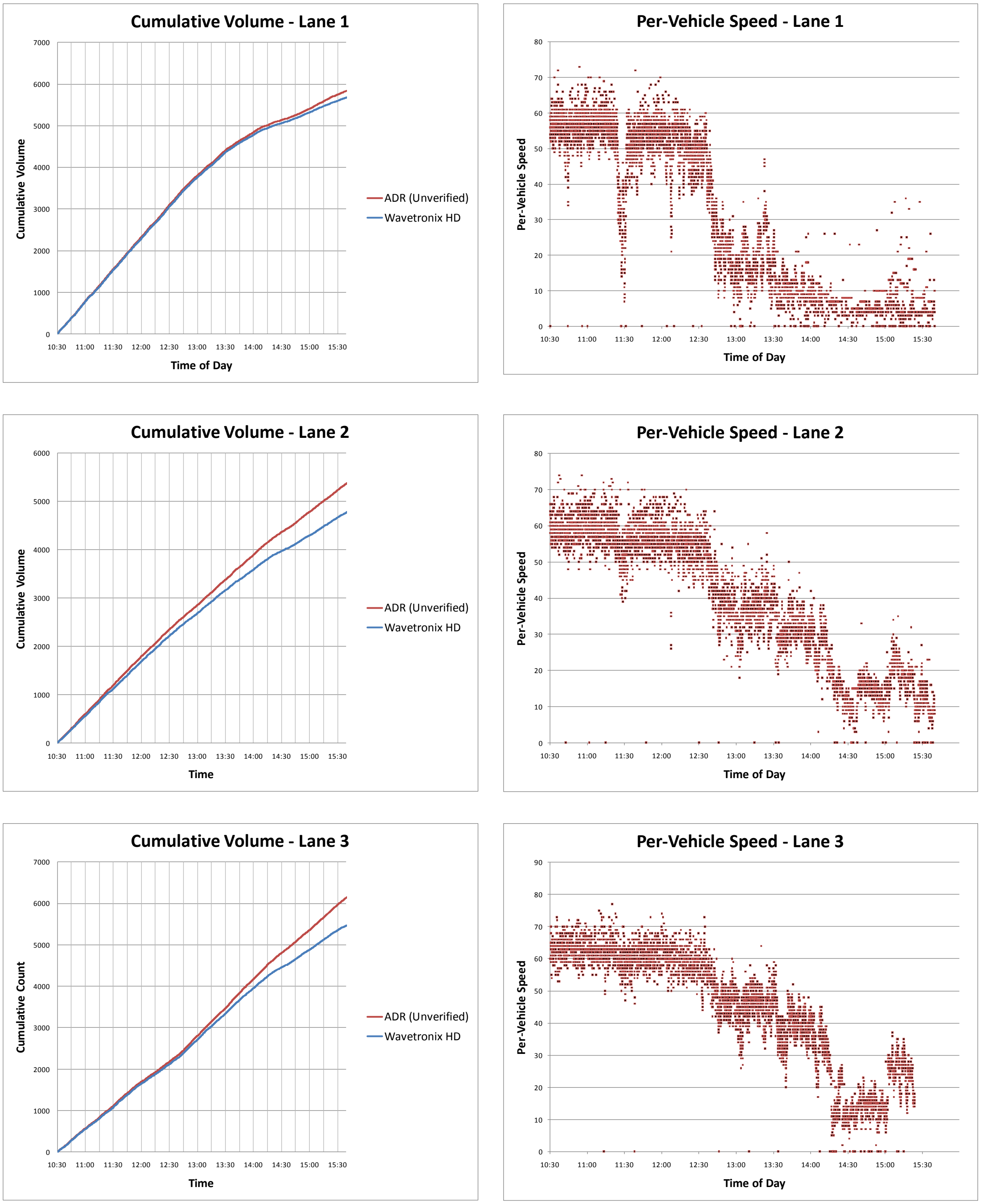


Figure 7. Wavetronix SmartSensor HD data captured on December 8, 2009 Traffic was unusually slow due to light snow conditions. Traffic undercounting in Lanes 2-3 (far two lanes) is attributed to occlusion from Lane 1 (lane nearest sensor).

After reviewing these findings with the vendor, it was learned that the Wavetronix SmartSensor HD has a built-in method to mitigate the negative effects of occlusion by scaling up volume when certain traffic flow characteristics are met. Thus, for example, when vehicles in the lane closest to the sensor have low speeds, traffic volumes in the occluded lanes are scaled up to adjust for vehicles the sensor does not detect. This feature has not yet been evaluated, but may be examined in future test activities.

In free flow conditions, occlusion is not a factor and volume accuracy is typically within 2 percent error. Table 11 shows the per-lane percent error. Note that the overall percent error is low, although the per-lane percent error is higher. It is common for lane changes to cause the sensor and baseline to place some vehicles in different lanes. The overall error is most important.

Table 11. Wavetronix SmartSensor HD Aggregated Volume Data (30 minutes, LOS B, 2010/01/20, 11:30 am-12:000 pm)

	Baseline	Wavetronix SmartSensor HD	Percent Error	Absolute Percent Error
Lane 1	663	674	1.7 %	1.7 %
Lane 2	530	516	-2.6 %	2.6 %
Lane 3	470	472	0.4 %	0.4 %
Total	1663	1662	0.0 %	1.6 %

Wavetronix SmartSensor HD – Speed

The Wavetronix SmartSensor HD reported speeds accurate to less than one mile per hour for free-flow traffic. It reported speed for 52 percent of the vehicles in Lane 1 and nearly 100 percent of the vehicles in Lanes 2 and 3. Other Wavetronix SmartSensor HD data sets were examined and it was found that most data sets reported speed values for 80 percent or more vehicles. Wavetronix explained that the lower speed capture rate is possibly due to additional energy reflected back from the roadway in the first lane due to the grass and paved shoulder. This higher reflected energy may cause the sensor to not trust as many of the speed measurements. Note that missing speed data does not affect volume accuracy. Typical data is provided in Table 12.

Table 12. Wavetronix SmartSensor HD Aggregated Speed Data (30 minutes, approximately 500-700 vehicles per lane, LOS B, 2010/01/20, 11:30 am-12:00 pm)

	Baseline	Wavetronix SmartSensor HD	Error	Absolute Error
Lane 1	57.8 mph	58.1 mph	0.3 mph	0.3 mph
Lane 2	60.9 mph	60.2 mph	-0.7 mph	0.7 mph
Lane 3	64.0 mph	63.4 mph	-0.6 mph	0.6 mph
Average	60.9 mph	60.6 mph	-0.3 mph	0.6 mph

Wavetronix SmartSensor HD – Classification

Two different types of classification performance were examined for the Wavetronix SmartSensor HD. The first was to compare length-based classes as reported by the sensor to manually classified axle-based classes. The second method was to compare length-based classes reported by the sensor to manually measured vehicle lengths from video.

Wavetronix SmartSensor HD – Comparison of Length-Based Classes to Manually-Determined Axle-Based Classes

The classification described in this section compares the axle-based classification from the PLP classifier to the Wavetronix SmartSensor HD lengths on a per-vehicle basis. The Wavetronix lengths were converted to the three length-based classes provided in Table 8. Although it is possible to define eight length bins, three bins were chosen to clearly separate passenger vehicles, single-unit trucks and multi-unit trucks. Additional classes would provide more granular data, but would not necessarily correlate with the FHWA 13-class scheme. The PLP baseline was manually verified for each truck.

The results of a 30-minute test were that the Wavetronix SmartSensor HD recorded 1659 vehicles throughout the period, including 118 trucks. The verified PLP baseline recorded 1668 vehicles including 85 trucks. A more comprehensive breakdown is shown in Table 14. The Wavetronix SmartSensor HD had errors with classifying single-unit trucks as large trucks and classifying passenger vehicles as single-unit trucks. These errors appear to be caused by a few specific issues. First, the selected break point between passenger vehicles and single-unit trucks is 23 feet. Of the 30 passenger vehicles that were incorrectly classified as trucks, the sensor measured 15 of these at 23-25 feet, pushing them into the single-unit truck classification. Information obtained by manual observation of the video reveals that this error was exclusively made on pickups and SUVs and large vans. Passenger cars likely do not give enough of a target area to be misdetected. There are a few examples where it appears that the misclassification was caused by multiple vehicles arriving at once. Examples are shown in Figure 8.

Table 13. Vehicle Classification Matrix for Wavetronix SmartSensor HD vs. Baseline.

		Wavetronix SmartSensor HD				
		PV	**SU**	**MU**	**Missed**	**Total**
Baseline PLP Classifier	**PV**	1538*	26	10	6	1580
	SU	3	44	10	0	57
	MU	0	0	28	0	28
“Ghost” vehicles		N/A*	3	0	0	3
	Total	1541	70	48		

Notes: PV is Passenger Vehicle, SU is Single-Unit Truck, MU is Multi-Unit Truck.
** This table does not account for the effect of balancing overcounting and undercounting passenger vehicles.*

Another source of error was when trucks were hauling a trailer. The Wavetronix SmartSensor HD generally does not detect a trailer as being separate from the primary vehicle. In this case, the sensor is accurately reporting the entire length of the vehicle/trailer combination. However, depending on how the data is used, it is often important to differentiate trucks from passenger vehicles. Even when hauling a trailer, the passenger vehicle does not load the pavement as significantly as a truck and some agencies would want to separate these vehicles from trucks. Figure 8 shows examples of passenger vehicles that were detected as long trucks. A summary of

SUV in Lane 3 (far lane) detected as a 25 foot vehicle.

SUV in Lane 3 (far lane) detected as a 24-foot vehicle.

Van in Lane 2 pulling a trailer that was classified as a truck.

Pickup truck in Lane 3 hauling a trailer that was detected as a large truck.

Figure 8. Sample Wavetronix SmartSensor HD misclassifications.

Table 14. Sample Wavetronix SmartSensor HD Classification Results (1/20/2010, 11:30-12:00)

Correctly Classified Trucks	Lane 1	Lane 2	Lane 3	Total
Large trucks (correct)	19	6	3	28
Small trucks (correct)	23	11	10	44
Total				72

Misclassified Trucks	Lane 1	Lane 2	Lane 3	Total
Large trucks (sensor classified as small trucks)	0	0	0	0
Small trucks (sensor classified as large trucks)	4	6	0	10
				10

Undetected Trucks	Lane 1	Lane 2	Lane 3	Total
Large trucks	0	0	0	0
Small trucks	1	2	0	3
				3

Non-trucks classified as trucks	Lane 1	Lane 2	Lane 3	Total
	18	9	9	36

SUMMARY	Lane 1	Lane 2	Lane 3	Total
Total passenger vehicles (sensor)	609	482	450	1541
Total passenger vehicles (baseline)	616	505	457	1578
Total passenger vehicles (sensor correctly classified)*	609	482	450	1541
Total trucks (sensor)	64	32	22	118
Total trucks (baseline)	47	25	13	85
Total trucks (sensor correctly classified)	42	17	13	72

Percent error (passenger vehicles)	-2.3%
Percent error (trucks only)	-15.3%
Percent error (total vehicle stream)	-3.0%

correctly and incorrectly classified trucks is given in Table 14. A full breakdown of correctly and incorrectly classified vehicles over the sample analysis period is given in Table A4 in the appendix.

Wavetronix SmartSensor HD – Comparison of Video Measured Lengths to Wavetronix SmartSensor HD Vehicle Lengths

In contrast to the axle-based classification, a test was run to compare Wavetronix SmartSensor HD length data to manually-measured vehicle lengths. This test was only conducted during free-flow traffic. This analysis disregards the type of vehicle and instead simply compares the length of the vehicle. It was found that for most vehicles, the Wavetronix SmartSensor HD reported a very accurate length. One outlier was a large Class 9 truck that the Wavetronix SmartSensor HD reported was 85 feet long due to grouping the truck (in the middle lane) with a passenger vehicle in the near lane, see Figure 9 with a following car in Lane 1. The Wavetronix records show that this vehicle did not appear on the Wavetronix PVR. As shown in the data, these cases were few. Because passenger vehicles tend to be similar sizes, emphasis was placed on manually observing additional trucks to develop a more even distribution of vehicle lengths.

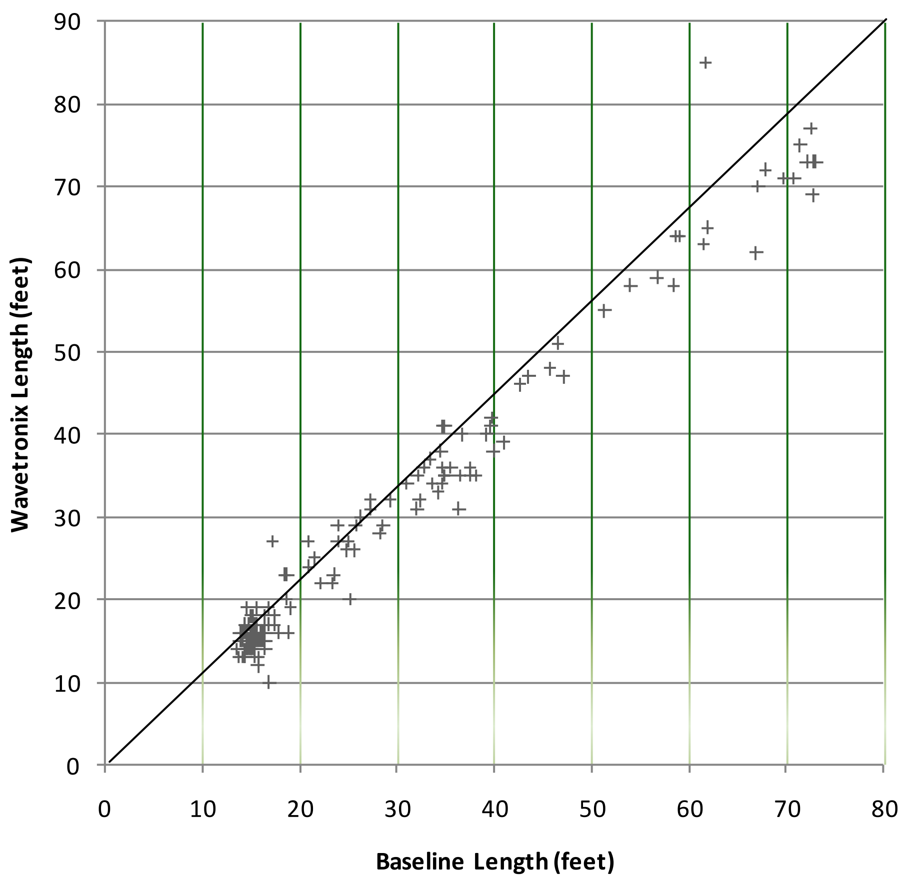


Figure 9. Baseline Length Compared to Wavetronix SmartSensor HD Length

The average error among passenger vehicles was 0.6 feet with an absolute average error of 1.6 feet. The average error for trucks was 1.7 feet with an absolute average error of 2.8 feet. These findings demonstrate that the Wavetronix can accurately determine vehicle length in free-flow traffic. The most significant error with length measurement is shown in Figure 10. The “outlier” point in Figure 9 (Wavetronix SmartSensor HD recorded it as an 85-foot long truck).

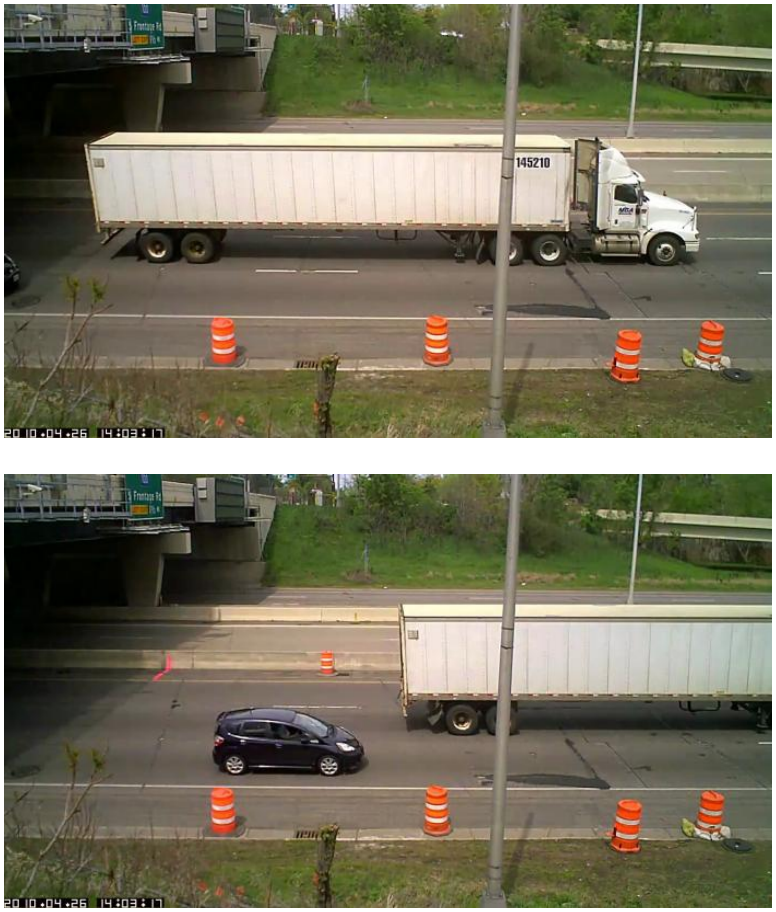


Figure 10. Screenshots of a Truck Grouped with a Following Car by the Wavetronix SmartSensor HD

<u>Wavetronix SmartSensor HD – Performance in Various Weather and Lighting Conditions</u>

The Wavetronix SmartSensor HD performs well in all weather conditions. The sensor was set to record data throughout the months of January to March 2010. The accuracy found during most weather conditions was consistent with performance during clear weather.

During this period, there were several days of extreme cold, rain, snow and fog. Data collected during a period of fog revealed a greater error, but still less than 5 percent error in traffic volume. There were not enough fog days available to determine sensor accuracy. Another issue that was found was that during periods with heavy snow accumulation, traffic tended to drive outside the marked lanes. This causes significant errors in the baseline data because vehicles do not drive over the piezos and loops. The baseline registers double counting in some lanes as the vehicles drove over two sets of piezos and loops. Despite these errors in the baseline, Wavetronix recorded consistent data even as snow accumulated on the sensor. During periods where snow did not accumulate and drivers stayed in their lanes, snow had no effect on sensor performance.

Because the Wavetronix SmartSensor HD is a sidefire sensor, it “views” the roadway and can assign vehicles that may be between lanes (due to a lane change) to one lane without double counting it. During periods where vehicles deviate from the marked lanes, the sensor can detect vehicles and assign them to a lane.

The Wavetronix SmartSensor HD performance was not affected by lighting conditions because the sensor has no reliance on optical light. The sensor performance was also unaffected by temperature and rain.

Wavetronix SmartSensor HD – Installation Findings

The Wavetronix SmartSensor HD has a relatively simple setup procedure. For the testing, the sensor was mounted at the recommended height of 28 feet at a 30-foot offset. This height was too high for an installer to install with a ladder, so the PNITDS (Portable Non-Intrusive Traffic Detection System) system was used. This system is a series of aluminum poles that can be attached at the bottom of an inplace pole and tipped up against the pole. To reach a height of 28 feet, three 8-foot poles were used in addition to the pole being mounted on a gradual slope. The PNITDS pole was secured with hose clamps. The installation is shown in Figure 11.

Figure 11. Wavetronix SmartSensor HD Mounted on Lighting Pole at NIT Test Site

Because the sensor was mounted for a semi-permanent installation so that it could record continuous data, power and communications were connected from the sensor to the shelter at the NIT Test Site. From the sensor, a multiconductor cable was run to the base of the pole. At the base, the cable was terminated on a lightning protection module within a polycarbonate base. Both serial and power were run from the base of the pole into the shelter with a 4-conductor cable. The other end of the cable was terminated on a lightning protection module in the shelter. A 9-pin RS-232 cable connected the computer to the module and 120V AC power was connected to the power supply. The entire run was about 150 feet.

Setup is critical to get good performance from the sensor. The sensor was pointed at the center of the applicable traffic lanes and the sensor was set so that it would be perpendicular to the passing traffic. Because the tip-up pole system was used, a few adjustments to the vertical and horizontal angle were made by tipping the pole down, adjusting it, and tipping the pole back into place. In order to verify that the horizontal angle is correct, a tool is provided in the SmartSensor Manager software. The tool shows a green arrow pointing from the sensor to the traffic to show that the sensor is pointed correctly. If the sensor is not pointed correctly, a red or yellow arrow is shown with an exaggerated view of how the sensor is improperly aimed so that the installer knows which way to turn the sensor. This tool eases sensor installation and was checked periodically throughout the months of testing to verify that the sensor was aimed properly. It never needed to be readjusted.

Once the physical setup was completed, the software setup was conducted with a personal computer. A PDA could also be used, but computers were available for this project. The main issue with software setup is that there must be enough traffic to let the "Auto Calibrate" tool function. At the NIT Test Site during the daytime, there is generally traffic in all three lanes, so the auto-calibrate procedure was quick. Once the three applicable lanes were available, other lanes were deleted to simplify and lessen the collected data set. Once set up, the computer or PDA may be disconnected and the sensor can store binned data, but not per-vehicle records. For this testing, the software was left connected so that per-vehicle records could be collected.

Overall, the Wavetronix SmartSensor HD is easy to set up and calibrate. Some special or permanent installations might require additional effort and the use of a bucket truck.

Wavetronix SmartSensor HD – Operational Findings

No operational problems were found throughout a long period of continuous data collection. The sensor sent serial data to the SmartSensor Manager software. The software wrote each PVR to a plain text file on the computer. Binned data was also collected.

The primary audience of the NIT project is the travel monitoring community who would generally use the Wavetronix SmartSensor HD's binned data functionality. There are no expected operational issues with this type of use. The sensor has adequate capacity for recording binned data. The data must be downloaded periodically so that the memory does not fill up.

For traffic operations applications, the sensor has capabilities for either being polled for the latest volume and speed data, or can record per vehicle records which could be further processed.

Wavetronix SmartSensor HD – Maintenance Findings

While the sensor was deployed in a season that has little chance of lightning, past experience has shown that it is important to install lighting protection for the sensor. Wavetronix produces modules for this use. The sensor is generally maintenance-free. Because the sensor is often mounted to a pole and could potentially shift due to vibration, it is recommended that the configuration be checked periodically to verify accurate sensor performance. The sensor needs no routine maintenance.

Wavetronix SmartSensor HD – Cost

Wavetronix provided budget pricing of $6,500, which includes the SmartSensor HD, mount and sensor cable. For a portable application, a mounting solution, such as the tip-up pole developed in the Portable Non-Intrusive Detection System (PNITDS) could be used. A power source, such as marine style batteries could provide power for use in a portable installation. Wavetronix said the sensor is maintenance free.

4.2 GTT Canoga Microloops

GTT Canoga Microloops – Volume

The microloops performed well in most conditions. As with others sensor set up in a speed trap configuration, at slow speeds, the sensor can drop vehicle presence between sets of tandem axles on common Class 9 trucks. Also, speed trap sensors have issues with detecting speed of slow-moving traffic.

Unlike the Wavetronix SmartSensor HD, the GTT Canoga Microloops are installed under the pavement and thus have no issues with occlusion. One item that affects sensor accuracy is lane changes causing double counting.

Overall, the data volume accuracy was within about 2.5 percent over the sample period as shown in Table 15.

Table 15. GTT Canoga Microloops Aggregated Volume Data (30 minutes, approximately 500-700 vehicles per lane, LOS B, 2010/01/20, 11:30 am-12:00 pm)

	Baseline	GTT Microloops	Percent Error	Absolute Percent Error
Lane 1	663	680	2.6%	2.6%
Lane 2	530	510	-3.7%	3.7%
Lane 3	470	475	1.1%	1.1%
Total	1663	1665	0.1%	2.5%

GTT Canoga Microloops – Speed

The microloops reported speed within less than one mile per hour when taken in aggregate. At free-flow speeds, good performance is expected because the microloops use a speed trap configuration. As long as the vehicle is detected at the same point on the vehicle (i.e. each of the pair of microloops is the same) as it crosses each microloop in the speed trap, a simple calculation will give an accurate speed. Care must be taken to set up the sets of lead and lag microloops so that they are parallel. If one speed trap has a different spacing, the timing will be wrong. If this were the case, an adjustment could be made in the software to mitigate this.

The vehicles in the sample test period were travelling at free-flow speeds and it is expected that most vehicles were driven at a uniform speed. However, in congested conditions, vehicles may be accelerating or decelerating as they pass the PLP baseline and microloops. The PLP baseline is about 50 feet upstream of the microloops which may not correlate well to the PLP baseline. If congested conditions prove to give erroneous data that is deemed to be due to the location of the sensors, only aggregate data will be considered. Table 16 shows the aggregated speed data that had less than one mile per hour absolute average error.

Table 16. GTT Canoga Microloops Aggregated Speed Data (30 minutes, approximately 500-700 vehicles per lane, LOS B, 2010/01/20, 11:30 am-12:00 pm)

	Baseline	GTT Microloops	Average Error	Absolute Average Error
Lane 1	57.8 mph	57.5 mph	-0.3 mph	0.3 mph
Lane 2	60.9 mph	60.9 mph	-0.0 mph	0.0 mph
Lane 3	64.0 mph	63.2 mph	-0.8 mph	0.8 mph
Average	60.9 mph	60.5 mph	-0.4 mph	0.4 mph

GTT Canoga Microloops Classification

As was done with the Wavetronix SmartSensor HD data, the Canoga Microloops Classification evaluation is separated into two parts. The first part compares the sensor's length-based vehicle classification to the traditional axle-based classification. The second part directly compares the length data that the sensor reports to manually measured length data.

GTT Canoga Microloops – Comparison of Length-Based Classes to Manually-Determined Axle-Based Classes

In contrast to the volume results, the classification shows that even though the count was accurate, not all the counted vehicles were classified correctly. The primary errors were truck misclassifications. Because the sensor detects magnetic changes, the ferrous components of the vehicle are detected and their prominence can affect the length that the sensor detects. For example, a pickup truck with a steel plow attached to its front end would be detected as a longer vehicle than it is. Conversely, a large truck with a high clearance between the bottom of the trailer and the surface of the pavement may be detected as a smaller vehicle than it really is. The primary error that the sensor had was to report vehicles was smaller than they really were. Small Class 5 trucks were the primary type of vehicle that was misclassified. Similarly, large Class 5 vehicles were sometimes classified as multi-unit trucks. Also, as with the Wavetronix SmartSensor HD, the sensor classified passenger vehicles and single unit vehicles hauling a trailer as multi-unit trucks. The summary is shown in Table 17. A detailed comparison of vehicle classification is shown in Table 18. Images of selected misclassifications are shown in Figure 12.

Another error that occurred a few times during the testing period was when the sensor grouped one vehicle closely tailgating another passenger vehicle as a large truck. The effect of this error was to undercount the total count by one (two PV counted as one MU truck), and overcount trucks by one. Some overcounting due to lane changes balanced this overcounting in the volume totals. A full breakdown of correctly and incorrectly classified vehicles over the sample analysis period is given in Table A5 in the appendix.

Table 17. Vehicle Classification Matrix for GTT Canoga Microloops vs. Baseline

		GTT Canoga Microloops				
		PV	**SU**	**MU**	**Missed**	**Total**
Baseline PLP Classifier	**PV**	1557*	18	5	0	1580
	SU	18	34	5	0	57
	MU	1	2	25	0	28
"Ghost" vehicles		N/A*	0	0	0	0
	Total	1576	54	35	0	

Note: PV is Passenger Vehicle, SU is Single-Unit Truck, MU is Multi-Unit Truck.
** This table assumes that balancing overcounting and undercounting passenger vehicles is acceptable.*

Table 18. GTT Microloop Classification Results
(30 minutes, LOS B, 2010/01/20, 11:30 am-12:00 pm)

Correctly Classified Trucks	**Lane 1**	**Lane 2**	**Lane 3**	**Total**
Large trucks (correct)	17	6	2	25
Small trucks (correct)	19	9	6	34
Total				59

Misclassified Trucks	**Lane 1**	**Lane 2**	**Lane 3**	**Total**
Large trucks (sensor classified as small trucks)	2	0	0	2
Small trucks (sensor classified as large trucks)	1	4	0	5
				7

Undetected Trucks	**Lane 1**	**Lane 2**	**Lane 3**	**Total**
Large trucks	0	0	1	1
Small trucks	9	4	5	18
				19

Non-trucks classified as trucks	**Lane 1**	**Lane 2**	**Lane 3**	**Total**
	8	8	7	23

SUMMARY	**Lane 1**	**Lane 2**	**Lane 3**	**Total**
Total passenger vehicles (sensor)	624	479	454	1557
Total passenger vehicles (baseline)	615	507	458	1580
Total passenger vehicles (sensor correctly classified)*	624	479	454	1557
Total trucks (sensor)	47	27	15	89
Total trucks (baseline)	48	23	14	85
Total trucks (sensor correctly classified)	36	15	8	59

Percent error (passenger vehicles)	-1.5%
Percent error (trucks only)	-30.6%
Percent error (total vehicle stream)	-2.9%

Small Class 5 truck classified as PV by the GTT Canoga Microloops.

Class 6 truck classified as PV by the GTT Canoga Microloops.

Long Class 5 truck classified as a MU Truck by the GTT Canoga Microloops.

Class 3 pickup truck classified as a SU Truck by the GTT Canoga Microloops because of the plow mounted on the front of the truck.

Tailgating passenger cars classified as a MU truck.

Tailgating passenger cars classified as a MU truck (Lane 1).

Figure 12. Sample GTT Microloop Misclassifications

GTT Canoga Microloops – Comparison of Video Measured Lengths to Wavetronix SmartSensor HD Vehicle Lengths

In contrast to the axle-based classification, a test was run to determine how close the Canoga Microloops would report to manually measured vehicle lengths. This test was only conducted during free-flow traffic. This analysis disregards the type of vehicle and instead simply compares the length of the vehicle. Because passenger vehicles tend to be similar sizes, additional trucks were examined to develop a more even distribution of vehicle lengths. Figure 13 shows a graphical representation of the baseline and sensor length comparison.

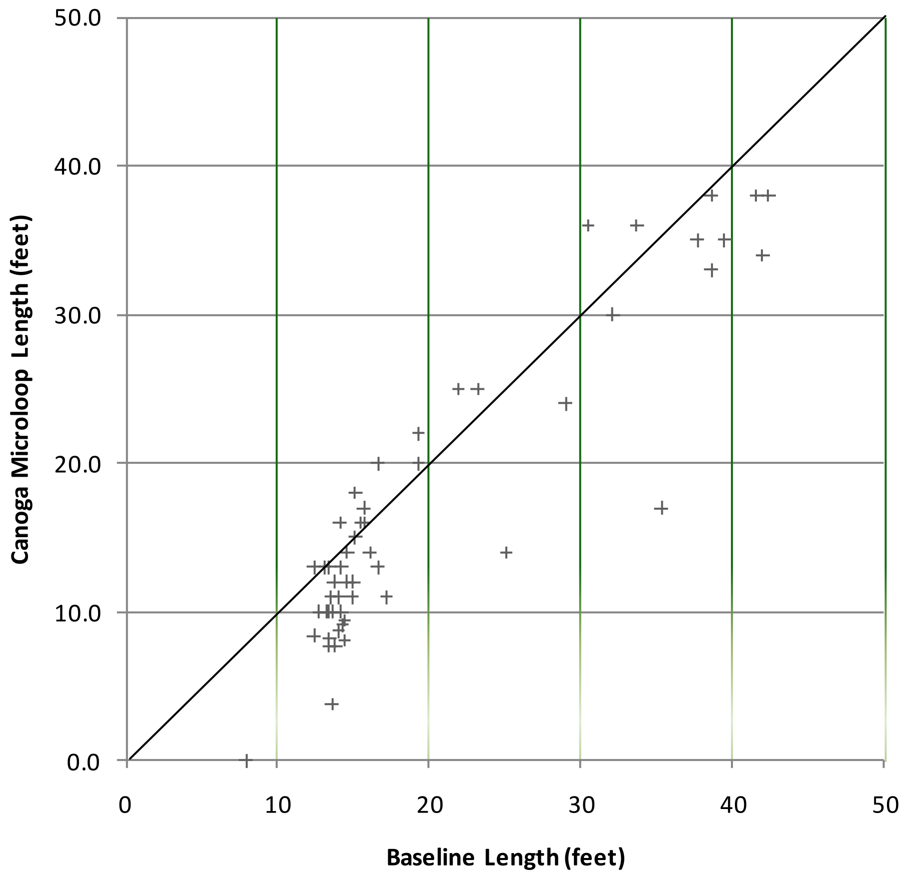


Figure 13. Comparison of Baseline Length to Canoga Microloops

The average error among passenger vehicles was -3.1 feet with an absolute average error of 3.7 feet. The average error for trucks was -2.0 feet with an absolute average error of 4.0 feet. The Canoga Microloops were reasonably accurate among a wide varied of different vehicle sizes, but there was significantly more variation when compared to the Wavetronix SmartSensor HD sensor. It is interesting to note that although there is a relatively tight distribution of passenger vehicles, the Canoga Microloops reported a rather large distribution of these vehicles. There were also some obvious outliers where the sensor vastly underreported vehicle length. A few examples are shown in Figure 14.

7.9-foot motorcycle measured at 0 feet long by Canoga Microloops.

35.3-foot SUV pulling trailer measured at 17 feet long by Canoga Microloops.

42-foot bus measured at 34 feet long by Canoga Microloops.

25.1 foot truck measured at 14 feet long by Canoga Microloops

Figure 14. Selected Vehicles That Canoga Microloops Measured Length Less Than Actual Length

GTT Canoga Microloops – Performance in Various Weather and Lighting Conditions

The Canoga Microloops had no performance degradation in any weather or lighting condition because they are mounted underground. As with the Wavetronix SmartSensor HD, long term data collection showed that other weather factors, such as temperature, had no effect as long as vehicles remain in the marked lanes. Because the Canoga Microloops are installed in the center of the lane, it is important that vehicles drive near the center of the lane. As with loops or piezos, lane changes can count as double detections.

GTT Canoga Microloops – Installation Findings

The installation of the Canoga Microloops used for this project was done in 2001 as part of The NIT Phase 2 project. Microloops were installed in bored conduit at a fixed depth under the roadway. After the conduit was in place, the Canoga Microloops were inserted into cartridges that are pushed into the conduit to position the sensor within the lane. These sensors were tested and found to report good data, so no additional deployment was necessary.

GTT was interviewed to explain a typical deployment and determine what deployment issues might be found. One critical question related to the installation of the sensors was whether the Canoga Microloops are truly a non-intrusive sensor. One concern was that in order to check that the sensor was installed at the right depth, the installer would have to go in the roadway and place a detector that would measure the conduit depth. Previous installations, including the 2001 installation at the NIT Test Site, have required this step to assure that the conduit was bored in the proper location. However, GTT reports that this step is no longer recommended or necessary. They require that the boring contractor has bore head locating equipment that reports depth within one inch per ten feet. Thus, the conduit should always be bored at the right depth. The sensors are tested and if they give the proper readings, the installer knows that the installation was successful. If the sensor does not work properly, the conduit would be re-bored, although GTT reports that this has never happened since they started requiring that the boring contractor has the locating capability.

GTT Canoga Microloops – Operational Findings

For this project, it was desired to capture per vehicle records. The ITS Link software that GTT provided allows this, although it does not have a way to automatically write this data to a file. Instead, the sensor spools data within the software which can later be exported to an XML file. One issue with this method is that the spooled data file can become very big and can crash the software upon stopping recording or saving the file. 24 hours of PVR did not crash the software. For the continuous data collection, binned data was recorded to avoid the crashing issue. Besides this issue, the software was stable. It is expected that the PVR function for this sensor would normally only be used for calibration and not for general use. The Canoga detector cards provide similar functionality to normal loop detector cards.

GTT Canoga Microloops – Maintenance Findings

The Canoga Microloops are maintenance free. However, as with standard inductive loops, it is recommended that they be checked and recalibrated periodically to account for changes in the electrical properties of the lead-in cable and sensor. Many agencies do not do this maintenance until a problem is noted. Also, because the microloops are buried 18 inches below the surface of the roadway, they are not susceptible to being damaged due to mill and overlay operations.

GTT Canoga Microloops – Cost

Three different types of microloops are offered by GTT with varying cost and performance. The triple-probe sensors were used for this project.

- Single probe sensors.
- Dual-probe sensors are able to detect lane changes better than the single probe sensors.
- Triple-probe sensors add the capability to detect motorcycles.

The quoted cost per triple-probe microloop is $585 and single probe cost is $204 (75-foot lead-in). The microloops must also be connected to a detector card. The GTT C944 card can be used with up to four microloops and costs $1,100. Thus, for a two-lane road with two detectors, the triple-probe microloops and detector card costs $3,442 (75-foot lead-ins). For a four-lane road with eight triple-probe microloops and two detector cards, the cost is $7007 (75 and 150 foot lead-ins). These costs could be reduced to $1,919 and $2,856 by instead using single probe sensors. These costs do not include installation including directional boring.

4.3 PEEK AxleLight

PEEK AxleLight – Volume

The AxleLight sensor was tested at the NIT Test site in LOS C traffic. The raw AxleLight volume performance was affected by vehicles being grouped together. The raw data showed that the sensor undercounted by 9.1 percent. However, two issues significantly affected the count. The first was that several vehicles grouped together because of how the LTPP classification scheme classifies 2S2 (two axles-space-two axles) vehicles. Under the classification scheme selected, the spacing of the last two axles is any distance up to 20 feet which allowed many tailgating passenger vehicles to be grouped as a 2S2 truck. In post-processing, this class was adjusted so that the final axle spacing for a 2S2 truck was only allowed to be up to 8.0 feet (exclusive). Once this adjustment was made, the data showed that the sensor undercounted by 5.4 percent.

Another issue was that because the sensor does not have a presence sensor, tailgating vehicles were grouped into vehicles that did not match any of the classes in the LTPP scheme. In this application, tailgating vehicles are defined as two vehicles with the rear axle of the leading vehicle within 45 feet of the leading axle of the lagging vehicle. This setting is user configurable, but the default value of 45 feet was recommended by the vendor. If this setting were to be set lower, the long trucks would be broken into multiple vehicles. When the sensor groups the vehicles, sometimes they fit within a given class and are classified. Other times, the vehicles do not fit any of the defined classes and the vehicles are given a default class. The LTPP scheme does not define the default class, but some schemes, such as the one PEEK provides, do have default classes (2-axle: Class 2, 3-axle: Class 2, 4-axle: Class 8, 5-Axle: Class 9, 6-axle: Class 10, 7-axle: Class 13, 8+ axles: Class 15). For the tests for this project, these default classes were separated from the valid classifications, but still counted toward the total volume. However, a grouping error, such as three closely spaced vehicles being counted as a 6-axle vehicle, was counted as one vehicle. To correct this error, the vehicles classified into the default classes were separated and broken apart as if they were 2-axle vehicles. For vehicles with odd numbers of axles, the remainder axle was counted as 2-axle vehicle because it was assumed that one of the axles was missed due to occlusion. Once these vehicles were broken apart into 2-axle vehicles, the sensor undercounted by 1.0 percent. This correction is a rough method of dealing with the grouped vehicles. It likely introduces an overcount of the vehicles that were grouped. However, this overcounting balances with the general undercounting of the sensor.

As a check to this correction, the total number of axles measured by both the baseline and AxleLight were compared. It was found that the AxleLight counted 3.4 percent fewer axles than the baseline across all lanes. In the first two lanes, the sensor counted 3.3 and 3.1 percent fewer axles respectively. However, the sensor counted 4.8 percent fewer axles than the baseline in Lane 3. This shows that occlusion had an effect in the sensor undercounting vehicles.

PEEK AxleLight – Speed

The PEEK AxleLight demonstrated very consistent speed data at a wide range of average speeds in 15 minute intervals. The graph in Figure 15 shows that the AxleLight consistently underreported speeds for the test examined. Note that the axes start at 35 mph and go to 65 mph. One caveat to this data is that the sensor was placed downstream of the baseline and it is possible that vehicles slow as they begin to climb the hill. The speed trap method that the sensor uses to determine vehicle speed should produce accurate results, but some unknown parameter caused it to underreport the data. The sensor spacing (distance from sensor to sensor) was set at 12.5 feet. This value was entered into the ADR 1000 during configuration. This error indicates that the sensors were about 4 percent farther apart than configured or about 1/2 foot.

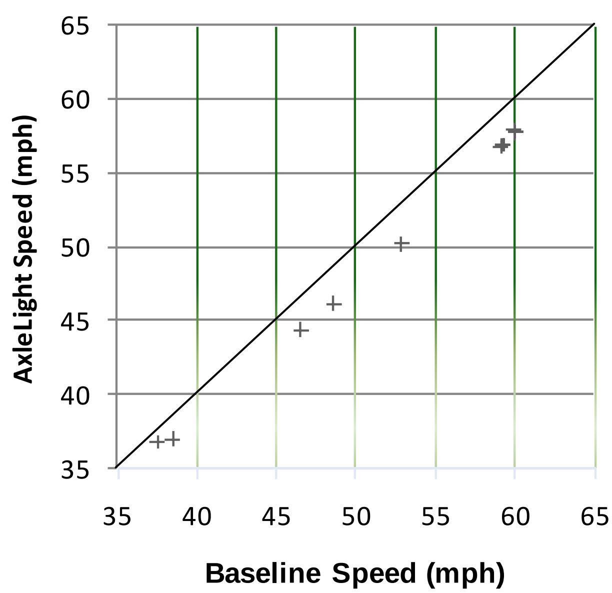


Figure 15. Baseline Speed vs. AxleLight Speed, Average Speed for 15 Minute Intervals

PEEK AxleLight – Classification

Axle-based sensor performance is based on detecting axle spacings. The axle spacings from individual PVR for several trucks were compared to the PLP baseline. This showed that the trend was toward the axle spacings being within 0 to 5 percent error for a wide range of axle spacings. However, there was significantly more variability with the detected axle spacings of a truck's tandem axles. This is due in large part to the smaller spacings leading to small errors being reflected as larger percent errors. Also, the resolution of the reported data was to the nearest tenth of a foot which explains the clusters of data points lower than 5.0 feet. Figure 16 shows the percent error for various axle spacings of selected trucks. Note that there is a wide distribution in percent error of axle spacings lower than 5 feet (tandem axles).

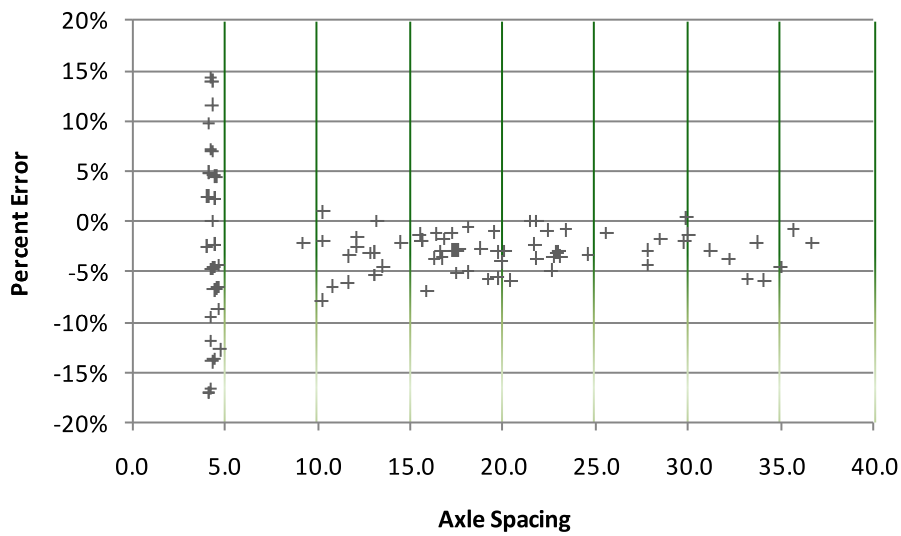


Figure 16. Percent Error of AxleLight at Various Axle Spacings

The key finding is that the sensor is capable of determining accurate axle spacings and making accurate classifications. For trucks that fit the classification scheme, the sensor generally classifies them correctly. However, a few complicating factors make the classification performance suboptimal. As explained in the description of AxleLight volume performance, tailgating vehicles with under 45-foot spacing are grouped. This causes trucks to be overrepresented and passenger vehicles to be underrepresented in the classification count. The impact on the passenger vehicle count is less significant than the truck counts because the number of these errors is small in comparison to the total correct classifications. However, the AxleLight recorded 152 6+ axle vehicles within the span of three hours where the baseline recorded only eight. These were misclassifications due to grouping.

PEEK AxleLight – Performance in Various Weather and Lighting Conditions

Due to logistical challenges, the AxleLight sensor was not tested in a wide variety of weather conditions. AxleLight is designed to be a portable sensor so it could only be left to collect data for periods of time of 48 hours or less. The AxleLight sensor was set out in multiple weather conditions, but due to unrelated issues, valid data was not captured.

Sensor setup was difficult in cold weather (snow and ice) conditions. At the NIT Test Site, plowed snow accumulates on the shoulder throughout the winter. An effort was made to dig out the plowed snow, but the sensor could not be mounted low enough due to the frozen ground. On a repeated attempt to dig low enough to make adjustments to the sensor, the area that was dug out had already been filled in with new snow and ice. Also, it was thought that the sensor might be damaged by plowed snow if it was left in place.

It was found that the sensor can detect vehicles in cold weather (below 32 degrees F). Additionally, because the sensor used could not be installed in a permanent or semi-permanent location, long-term data collection periods that would have included multiple weather conditions could not be assessed.

PEEK recommends that the sensor not be set out in heavy rain conditions where there is significant road spray because the sensor would detect water kicked up by wheels as extra axles. Deployment in heavy rain conditions was not feasible during the test period.

PEEK AxleLight – Installation Findings

The AxleLight was primarily designed to be a portable sensor. The most common way to mount the sensor is to attach it to guard rail. Other methods are possible, such as an installation done by Iowa DOT that places the sensor in a roadside cabinet, using the sensor to create a permanent ATR station.

PVR data collection proved to be problematic with the sensor. The sensor has the capability to generate this type of data, although the PEEK ADR 1000 that was used to capture the data did not have enough memory to record the entire duration that the sensor was set out (48 hours).

The sensor was sent in two large cases. These cases contained all the equipment required to set up the sensors. The mounting brackets must be assembled for each deployment. If moving from site to site, it would be possible to save some set up time by not fully disassembling the mounting brackets. The sensor takes about one hour to fully set up.

An important step is to measure the distance between the sensors because the length and vehicle speed are based on this parameter. This is difficult to do with only one person because the tape measure tends to tug at the sensor, pulling it out of alignment. It is difficult to lock the sensor down firmly enough to avoid this. However, allowing for a small amount of inaccuracy would be possible if only one person is installing the sensor. For this project, two people were always available for installing the sensor to avoid this issue and to expedite setup.

Figure 17 shows the AxleLight set up at the TH 52 Test Site. Physical setup must be done with extreme care to make sure that the sensors' lasers are pointed as close to the roadway as possible without hitting the crown of the road. There are vertical height, vertical angle, and horizontal angle adjustments which interrelate and must be both individually adjusted and then readjusted to accommodate the other aiming parameters. An iterative process must be followed to optimally aim the sensor. It is important to spend an adequate amount of time adjusting the sensor so that the laser is as low to the roadway as possible without hitting the crown.

The software setup was straightforward, but involved many steps. Making an error on any of the steps could compromise the quality of the data. Several of the initial setups done for this project had a small error or something that was not fully understood, leading to poor data quality or erased data. For example, it was found that when a new day was started while recording PVR, the previous day's records were erased. Additionally, some guesswork or knowledge of the roadway geometrics is needed to get a proper installation. The sensor asks the user for a fixed lane width. The auto-calibrate function automatically detects the first traffic lane and then adds the user-configured lane width to calculate the location of subsequent lanes. This method usually works, especially if the user can estimate whether the auto-calibrated values are approximately correct. However, an error could be introduced if the auto-calibration makes an error and the user does not correct it.

The sensor has the capability to detect traffic in two directions, although it was very difficult to get a proper physical setup that could detect all four lanes at the TH 52 site. It was somewhat easy to make physical adjustments to optimize one of the directions, but multiple directions were more difficult. Because of this difficulty, this project only used data in one optimized direction of travel. Data for the other direction was captured, but excluded from the analysis. It is assumed that with significant setup time, on certain roadways, it would be possible to collect good data in two directions.

There are a few ways to check the quality of the data. The first is the "array monitor." This allows the user to see a pair of sensors in each lane and view the cumulative axle count. Both the lead and lag sensors in each lane should record the same number of axle hits. If the number is not equal, it might indicate that one of the sensors is mounted too high and is counting phantom axle hits when the laser hits a non-axle component on the underside of a truck. The axle hits should reflect the number of axles that pass in each lane. The sensors can be physically adjusted to correct these problems. This can usually be done without changing the sensor configuration, although major changes in physical setup, such as remounting the sensor on a different post should be followed by a new configuration.

Once the "array monitor" is giving the same values for both the lead and lag for each array, the "vehicle monitor" and "event monitor" can be viewed to make sure vehicles are counted and classified correctly. The PEEK ADR 1000 can show various data on each vehicle, but only

AxleLight mounted to guard rail at TH 52 Test Site.

View from AxleLight sensor.

Two AxleLight sensors set up in a speed trap configuration.

AxleLight, PEEK ADR 1000 and battery module.

Figure 17. TH 52 Test Site AxleLight Deployment

displays the past three vehicles at a time. Thus it can be difficult to keep an accurate count, although monitoring for big trucks can be useful.

PEEK AxleLight – Operational Findings

As mentioned, there was some difficulty with collecting PVR from the sensor. As data collection time was running low, a computer was connected to the ADR 1000 and the ADR was set to output event data over the serial connection that was captured on the computer. For typical traffic data collection use, this setup would be undesirable, although it could have a use for permanent deployments that require PVR recording.

Typical traffic data monitoring applications do not require per vehicle records, so it is anticipated that in standard operations, the difficulty in recording per vehicle records would not be encountered. The ADR 1000 is capable of capturing long durations of binned data among all classes and data recording should not be problematic. Another strength of the integration with the ADR 1000 is that many agencies will already be familiar with the equipment because the same hardware has been used for traditional tube counts for several years.

Once set, the AxleLight operates until the batteries connected to the sensors deplete. Each AxleLight sensor has a battery pack connected to it that lasts for about 48 hours on a full charge. These batteries are 12-volt with about 12 aH capacity and are encased in a polycarbonate case. With the provided battery chargers, it requires over 8 hours to fully charge the batteries. The ADR is internally powered and lasts longer than 48 hours.

PEEK AxleLight – Maintenance Findings

Because the AxleLight was designed to primarily be a portable sensor, only typical cleaning is required. As with most applications which require battery power, it is recommended that the batteries be replaced periodically depending on the amount of use. With heavy use, the batteries should be replaced approximately every two years. Batteries could be replaced by the user with an off-the-shelf battery of a similar size and capacity or PEEK could assist with this replacement.

PEEK AxleLight – Cost

The manufacturer’s suggested retail price for the AxleLight system is $31,580. This cost provides a complete portable system, similar to what was provided for this evaluation. The portable system would be mounted to existing roadside infrastructure, such as guard rails.

PEEK claims that the sensor is maintenance-free, although the batteries would need to be periodically replaced (replacements are available from PEEK). Batteries are expected to function well for at least two years with regular use.

4.4 TIRTL

TIRTL – Volume

The TIRTL performed consistently in volume data collection, but at slow speeds, and especially if the sensor is covering several lanes, there is a possibility that vehicles with large wheels will occlude other lanes. The scatter plot in Figure 18 shows that across many volume levels, the sensor generally accurately reports volume. Among the entire test duration, sensor undercounting and overcounting balanced to give a final percent error of 0.4 percent. There was a general trend of overcounting with a median overcount of 2 percent per hour period. A few periods of undercounting balanced this overcounting, but no specific cause of this undercounting could be identified. The periods were from 1:00 pm to 3:00 pm and 12:00 am to 6:00 am. No environmental cause could be linked to these times. All percent error for other time periods were within one standard deviation. The system has an alarm system that could be used to diagnose volume issues in future deployments. The finding from this test was that the TIRTL generally reports volume within 2 percent of the baseline, but a few outliers of unknown cause produced errors.

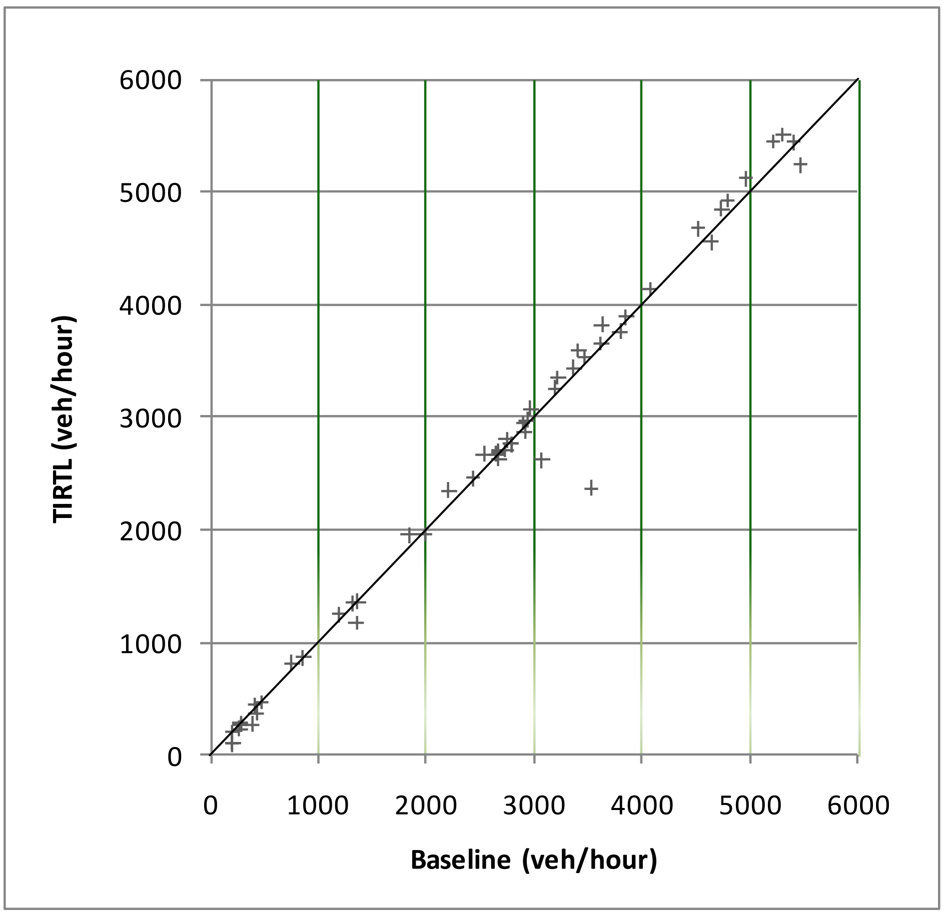


Figure 18. Baseline Compared to TIRTL Volume
All Lanes, LOS A-B, TH 52 Test Site

TIRTL – Speed

At both free-flow and speeds, the TIRTL is capable of measuring accurate speeds. Average speeds for 15 minute intervals were compared to baseline speeds measured by the TH 52 WIM site. The comparison of these aggregate speeds are shown in Figure 19. Note that the axes in this graph are centered around the average free flow speeds. The average error throughout the entire tested period was 0.7 mph higher than the baseline speed. The absolute average error was found to be 1.2 mph. This shows that the TIRTL can consistently report accurate speed in free flow traffic. The manufacturer claims that TIRTL can provide accurate data at speeds as low as 5 mph.

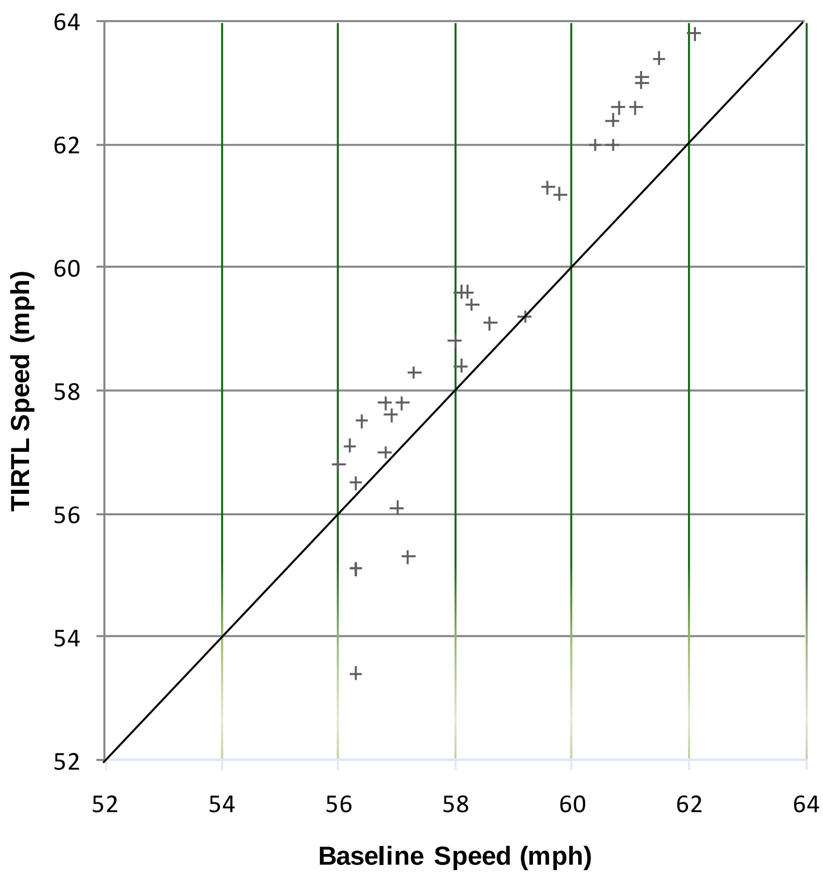


Figure 19. Baseline Speed vs. TIRTL Speed, Average Speed for 15 Minute Intervals

A separate test was done to determine how well the TIRTL matched the baseline speeds at the NIT Test Site in congested traffic. The graph in Figure 20 shows that the TIRTL speed matched the baseline speed well in both free flow and congested traffic conditions. Note that the baseline data (shown in blue) has some outlier points that are shown in the graph (spikes with high or low values). These points are where the baseline inaccurately measured a vehicle due to multiple vehicles being over the sensors. The TIRTL sensor had fewer of these types of errors than the baseline presumably because it does not use a traditional speed trap method to determine vehicle speeds.

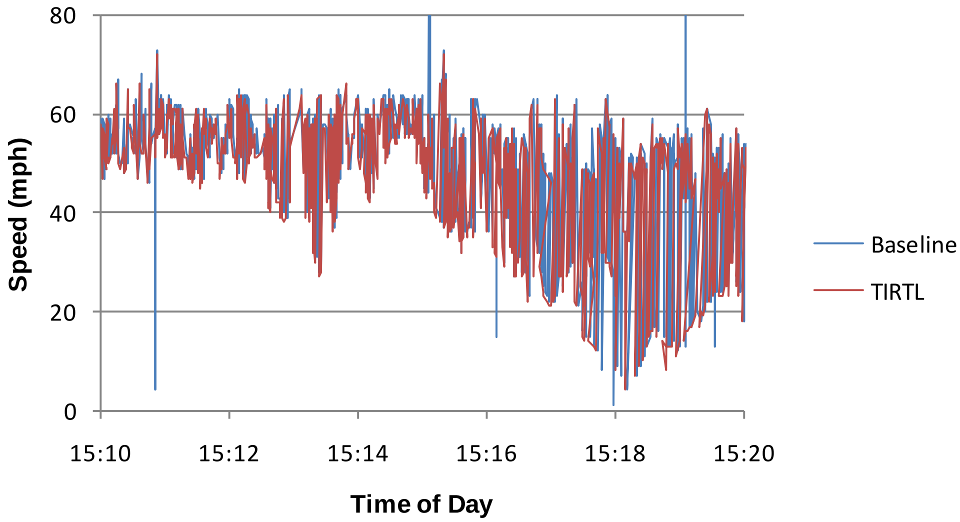


Figure 20. Comparison of Baseline Speed to TIRTL Speed, Congested Traffic All Lanes at the NIT Test Site

<u>TIRTL – Classification</u>

The TIRTL classification performance was tested at the TH 52 Test Site over all four lanes (two lanes in each direction with a ditch median). Two different tests were conducted to determine the sensor's classification performance. The first was a comparison of baseline axle spacings to the sensor reported axle spacings. The other was a comparison of volumes count per axle-based bin.

Axle Spacing Accuracy

The sensor reported axle spacings within about 2 percent of the actual axle spacing measured by the baseline. This performance did not vary significantly across various axle spacing lengths. The measurements were taken on large trucks passing at free flow speeds. Figure 21 shows the distribution of axle spacing percent error. Table 19 shows a summary of the percent error.

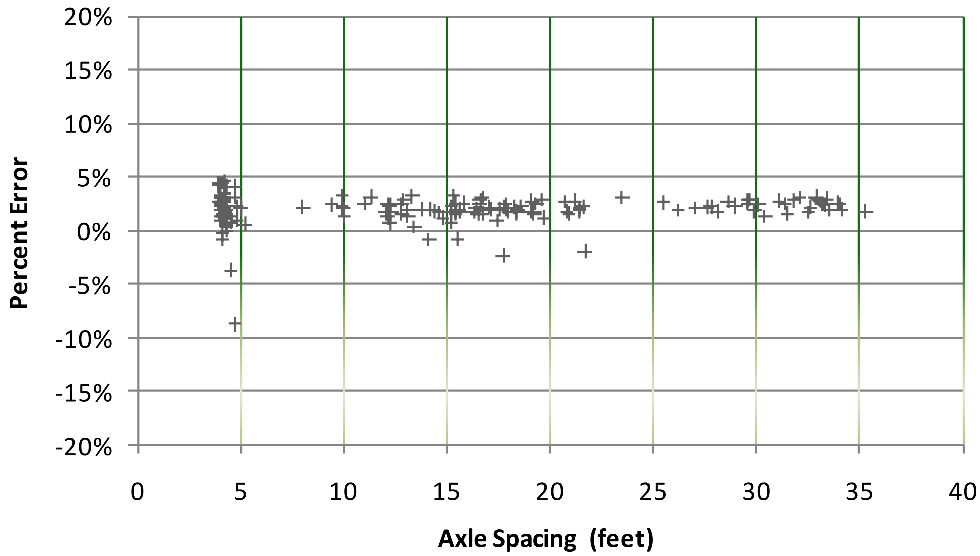


Figure 21. TIRTL Axle Spacing Percent Error

Table 19. Percent Error by Axle Spacing Group

Axle Spacing (feet)	Number of Samples	Average Percent Error	Absolute Average Percent Error
0-10	75	2.0%	2.4%
10-20	61	1.8%	2.0%
20-30	23	2.1%	2.3%
30-40	18	2.4%	2.4%

Classification by Axle Count

To more completely test the classification performance, vehicles were binned by the number of axles counted. The LTPP class scheme could not be used because the TH 52 WIM (baseline) had Mn/DOT's classification scheme which differed from the sensor scheme. The baseline and TIRTL data was put in one hour bins by number of axles and the scatter plots shown in Figure 22 shows how the sensor data matched the baseline. The 2-axle and 5-axle vehicles matched the baseline well due to the large number of vehicles within those bins. However, the 3-axle and 4-axle comparisons revealed that those bins were significantly overcounted. Some of these errors can be attributed to the grouping issue as explained in the Peek AxleLight classification section. In order to make the results between the baseline (TH 52 WIM) and the sensor comparable, the Mn/DOT classification scheme was loaded on the TIRTL. The manufacturer claims that the classification scheme developed for the TIRTL would avoid these errors. However, after testing, the manufacturer's classification scheme was reviewed and found to be less robust than the

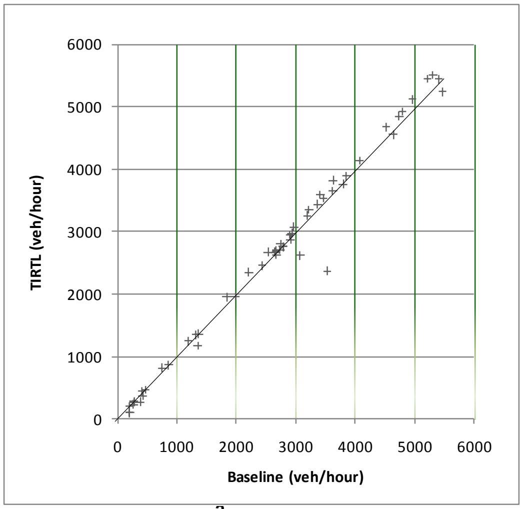
Mn/DOT and LTPP scheme, but tailored to specific classification issues related to the TIRTL. It is recommended that future testing use the TIRTL classification scheme. To avoid misleading comparisons due to this fact, the following analysis focuses on axle counts and spacing, rather than purely on classes.

The 3-axle and 4-axle classification data was reviewed to determine how prevalent the vehicle grouping issue was. Few instances of two passenger vehicle grouping into a 4-axle vehicle were found. An average of 2.2 vehicles per hour (9:00 am to 24:00) were likely two passenger vehicles that were grouped into a 4-axle vehicle. The 3-axle misclassifications may be multi-axle vehicles that were broken into smaller vehicles due to occlusion. Because of the relatively small number of 3-axle vehicles, misclassifications such as these can have a major effect on the data. Although there were not many 6+ axle vehicles, the sensor generally undercounted these vehicles, and rarely overcounted them due to grouping.

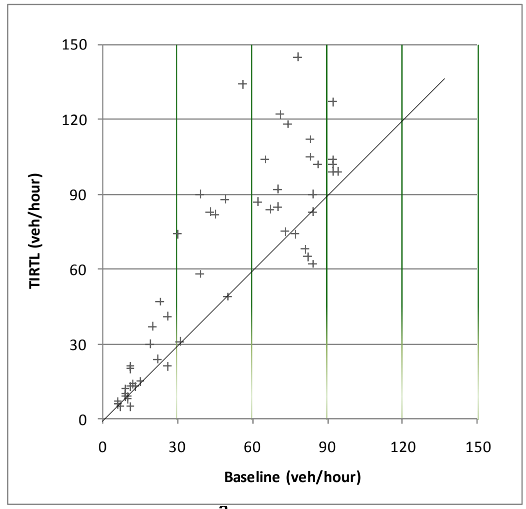
For the data shown in Table 20, the periods where unexplained erroneous data were removed.

Table 20. TIRTL Axle Counting Percent Error by Axle Bin.

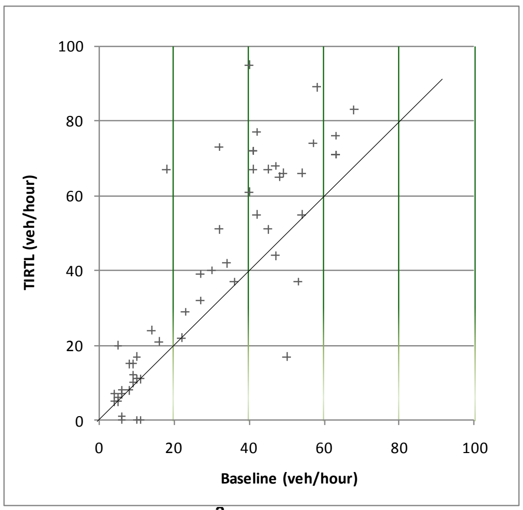
Axle Bin	Average Percent Error (One Hour Bins)	Average Absolute Percent Error (One Hour Bins)
2-axle	1.7%	2.7%
3-axle	36.7%	39.7%
4-axle	44.0%	44.3%
5-axle	-3.8 %	6.3 %
6+ axles	-0.8%	20.0%



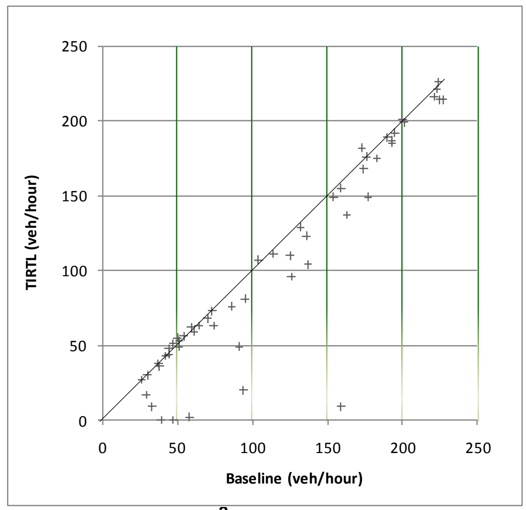
2-axle vehicles. r^2=0.985.



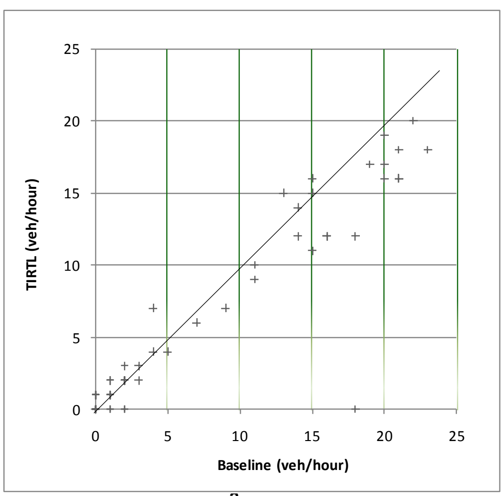
3-axle vehicles. r^2=0.767.



4-axle vehicles. r^2=0.734.



5-axle vehicles. r^2=0.871.



6+ axle vehicles. r^2=0.872.

Figure 22. Comparison of Baseline Volume to TIRTL

TIRTL – Performance in Various Weather and Lighting Conditions

Due to scheduling and logistical challenges, the TIRTL sensor was not tested in a wide variety of weather conditions. Because the sensor was obtained late in the testing period, it was not possible to test the sensor in extreme cold temperatures or with snow. Additionally, because the sensor used could not be installed in a permanent or semi-permanent location, long-term data collection periods that would have included multiple weather conditions could not be assessed.

However, an effort was made to test the sensor in rain conditions. The TH 52 site had adequate drainage, so the test that was conducted during a rain event showed that rain did not affect sensor performance. Performance in rain conditions varies depending on the site. While falling rain has no or a small effect on sensor performance, road spray can occlude the laser. Wheel path rutting, ponding or extremely heavy rain can cause road spray significant enough to degrade sensor performance.

TIRTL – Installation Findings

Finding a suitable test location and the amount of time required to set up the system were the two primary installation issues noted. The TIRTL is required to be placed on each side of the subject roadway. One such installation is shown in Figure 23.

Because the TIRTL system was used in temporary deployments, traffic delineators and barrels were used to house the system, provide some traffic control and protect the sensors from traffic. At the TH 52 Test Site, a series of five delineator cones were set on each side to taper the

Figure 23. Traffic Control for TIRTL Mounted on the Roadway Shoulder

shoulder toward the roadway to protect each of the two TIRTLs. Also, two traffic barrels were used on each side of the road; one held the TIRTL (with a cut out section for the sensor's laser to point out) and the other held a marine-style battery (C-size batteries internal to the TIRTL could have alternatively been used). The TIRTL can also be powered by C-sized batteries held internal to the sensor, but the external battery was used to make sure the sensor would run for long durations. Additionally, advance warning signs that said "ROAD WORK AHEAD" were placed upstream of each sensor. Sand bags were used to hold the sensor barrel and signs in place. All this equipment proved to be more than could be carried in a full-sized pickup truck. Multiple trips were required to deliver the equipment to the site. The equipment was left on site during the approximately one month of testing.

Setup of the traffic control equipment took approximately 30 minutes with another 20 to 30 minutes to take the traffic control equipment and sensor down after testing. Figures 24 and 25 show the traffic barrel and TIRTL base.

Figure 24. Traffic Barrel with Cutout for TIRTL Sensor.

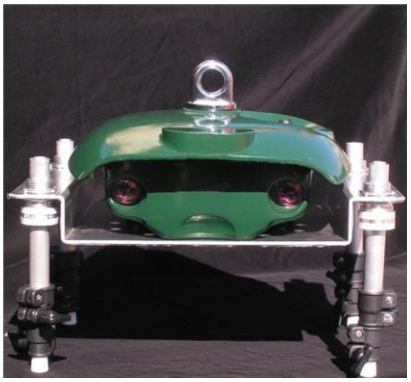


Figure 25. TIRTL Base

Additionally, the sensors each needed to be set up and aimed as shown in Figure 26. Mn/DOT's system was purchased in 2004 when the system came with optical scopes. A person could look through the scope (from the top of the sensor) to sight in the TIRTL on the other side of the roadway. Small adjustments could be made to the aiming, although over a long distance, such as 80 feet, a small adjustment in the TIRTL base skewed the sensor significantly. It was sometimes more effective to shim the traffic barrel base that the sensor was set on. A laser aiming tool is available now. This tool has a laser that is mounted to a machined piece that fits in the two mounting holes on the top of the sensor. Someone would hold a target, such as a piece of paper, on the other TIRTL to show where the laser is hitting. This method has proven to be more effective than the optical scope method. Also, the laser method allows for the sensor to be mounted inside a cabinet where there is not enough room for a person to use the optical scope. The manufacturer claims that setup with the laser aiming system and the new portable cabinets can be done in ten to 20 minutes.

Figure 26. TIRTL Setup--Aiming With Scope

All but one of the tests were run at the TH 52 site because the NIT Test Site required a lane closure for setup. For the NIT Test Site setup, the inside eastbound lane of I-394 was closed to traffic while the sensor was set up. The setup at the NIT Test Site required additional time because the roadway is very flat and there is a full curb on the right shoulder. At some sites, the sensor could be mounted on the curb with the base set very low, but when this was tried at the NIT Test Site, it was too high for the sensor to avoid detecting non-axle vehicle components hanging from the bottom of trucks. Thus, the sensor and traffic barrel housing it were placed directly on the roadway shoulder. Even this was found to be too high, so the base of the traffic barrel was removed to allow the TIRTL base to sit directly on the roadway. To accommodate this lower positioning, the traffic barrel was further cut so that the lasers could point out of the barrel. An alternative mounting method that the manufacturer now recommends is shown in

Figure 27. This system uses two 12-volt rechargeable batteries which are charged with a 12-watt solar panel integrated with the cabinet. The threaded legs can be cut to specified length. The threads allow for fine adjustments to the height and tilt. The visible green laser recommended for sensor aiming is shown in the leftmost image.

Figure 27. TIRTL with Portable Enclosure

Through interviews, it was found that most agencies that are using the TIRTL are doing so with a permanent or semi-permanent installation where these unknowns have been solved. It is recommended that an initial site survey, including a cursory setup, be done.

During the course of the project, two solutions for permanent or semi-permanent were suggested. The first was to mount the TIRTL in a small cabinet placed on the side of the road. This cabinet protects the TIRTL and could provide additional capacity for batteries. These cabinets should be installed outside the clear zone or otherwise be protected. The TIRTL vendor supplied photos of other permanent installations of both barrier-mounted units (Figure 28) and roadside mount units (Figure 29).

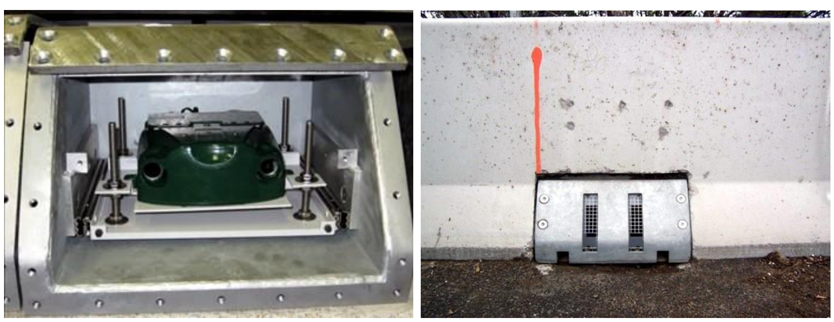


Figure 28. Barrier-Mounted TIRTL Sensors (Permanent Installation)

Figure 29. Roadside/Pad-Mounted TIRTL Sensors (Permanent Installation)

Another suggested method is to mount the sensors to poles located outside the roadway as shown in Figure 30. It is reported that a pole-mount configuration has worked for Illinois DOT, although it was not tested for this project.

Figure 30. TIRTL Pole Mount Examples (Permanent Installation)

For sensor setup, the primary objective is to align the sensors so that the two TIRTL units are pointing at one another such that they are the proper height above the road and are not tilted. To aid with this, the TIRTLSoft software that is provided has a few tools to assist in alignment. One is the "Beam Levels" that show how strong the beam strength is. The values should be both high and approximately equal. Another is the tilt setup. As vehicles pass the sensor, dots are shown on a graphical display that show whether the sensor is tilted too much either way. Adjustments can be made and the graphical interface can be reset after each adjustment as needed. The final setup tool is a height setup that shows the approximate height of the sensor. It is important that the sensor is not installed too high because it could detect non-axle components of trucks as phantom axles, leading to a misclassifications. Once the sensors are aligned, the sensor auto-calibrates. Data is reported once the auto-calibration is complete. There is a traffic reporting utility that allows the operator to see how live traffic is reported. It can show all lanes or just user-specified lanes. It is recommended that this utility be used to examine all lanes independently before leaving the sensor to record data. The primary way to set up the sensor offers no way to manually define lanes, but the sensor adequately automatically determining lanes. The only recourse a user would have if the auto-calibrate does not work properly is to re-aim the sensors.

Despite the availability of these useful tools, the sensor does not record the quality of the setup. It would be possible for an inexperienced user to quickly set up the sensor and record data, but have no assurance of the quality of the data. This is a common issue with any type of sensor, but particularly with the TIRTL unit, which is susceptible to phantom axle hits.

TIRTL – Operational Findings

Only the on-board traffic data collection method was tested and it was found to be effective for recording PVR. An issue was found with downloading PVR at a slow rate, but the TIRTL vendor said that the "Compressed Logs" function was developed address this. This recommendation was made after testing was completed, so this method could not be evaluated. All current TIRTL training recommends using the “Compressed Logs” function.

TIRTL – Maintenance Findings

Because the TIRTL was mounted on the road shoulder, it was susceptible to road spray. If not used with a portable cabinet, it is recommended to clean the lenses monthly if the sensor is in heavy use near the roadway. For installations where the sensor is well off the roadway, this is likely not as necessary and the lenses could be cleaned as needed or at least yearly. However, according to the vendor, all new TIRTL applications use a cabinet. The vendor recommends that the sensor lenses or housing be cleaned each time a setup is taken down. For permanent applications, a beam strength alarm notifies the user when it is needed to clean the lens or housing.

TIRTL – Cost

TIRTL’s United States distributor, Control Specialists Company, provided cost information. This information is applicable to the “version 2” TIRTL system that is comparable to the “version 1” system, but offers more communications functions. These costs apply to both a portable or permanent system, although installation costs are not included in this figure.

The TIRTL “version 2” system costs $21,475 which includes, the transmitter, receiver, software, “PRN Converter” (program which converts Vehicle by Vehicle output to industry standard binned data), two power cables, GPS cable, “mobile cable,” green laser sight, hockey puck antenna, on-board integrated cell modem (GSM) and GPS. A TIRTL with a PSTN costs $24,950.

Additionally, Control Specialists Company provided a quote for Portable TIRTL enclosures that could be used to protect the TIRTLs on a roadside portable application. Two enclosures cost $3,460 and includes a flush mount 12-watt solar panel, locking cabinet, solar regulator, charger and legs with leveling feet

4.5 Miovision

Miovision – Volume

The Miovision sensor collected volume data to within the accuracy of the baseline measurement (2 percent). As with other sidefire sensors, occlusion is an issue. Slow speeds have no effect on sensor performance except when large, slow-moving vehicles occlude lanes farther from the sensor.

Miovision – Mainline Freeway Volume

The Miovision sensor was set up at the NIT test site on a pole approximately 30 feet from the edge of travelled lane. A screenshot of the Miovision camera's view can be seen in Figure 31.

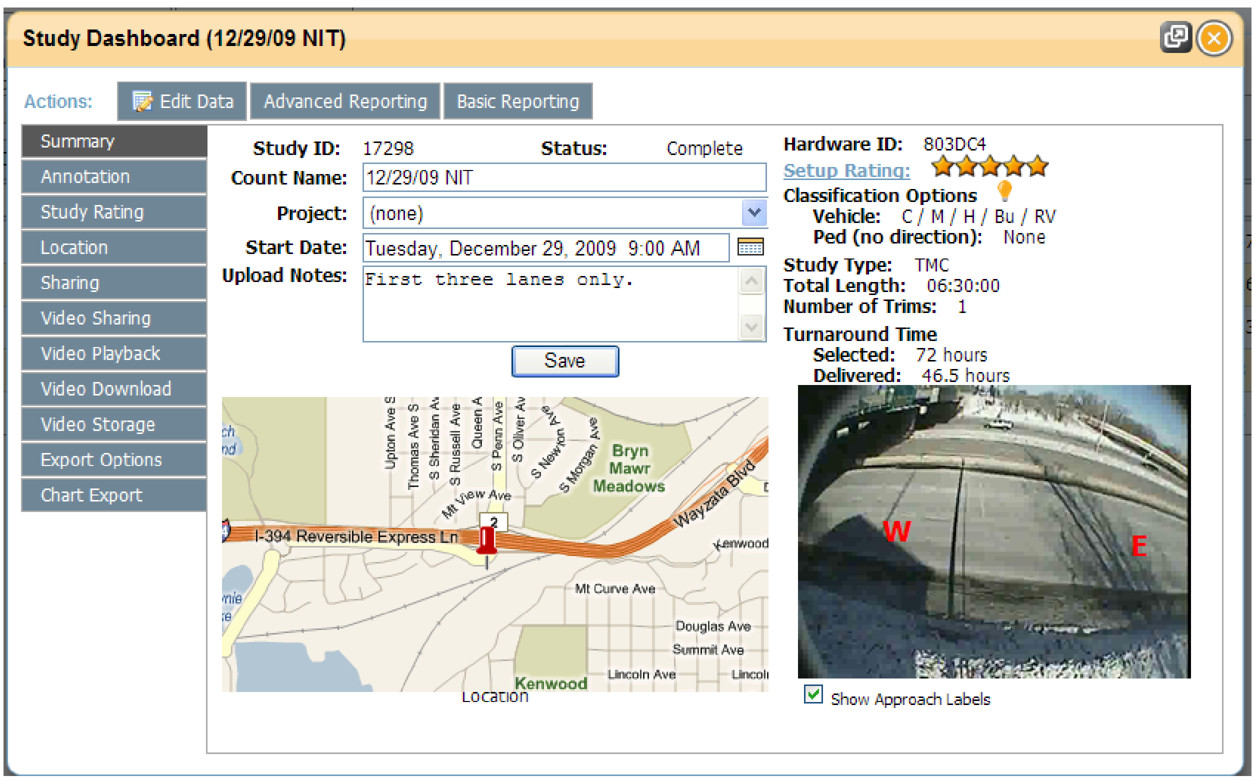


Figure 31. Online Interface for Miovision Mainline Freeway Test

The results of the comparison to the unverified ADR baseline were that the sensor undercounted by about two percent. However, the unverified ADR baseline has proven to inconsistently overcount due to lane changes. To take a sample of the overcounting during this test period, the first half hour of data was manually verified. This verification step removed 36 overcounted vehicles that were primarily due to lane changes (approximately 2.0% of the vehicle unverified PLP ADR volume). Presumably, if this error is consistent throughout the test period, the PLP ADR volumes would be about 2% lower. However, as noted, the overcounting is inconsistent and may not be uniformly applied for the final analysis. The sensor is configurable to report data in bins of one minute, five minutes, ten minutes, 15 minutes, 30 minutes or 60 minutes. A comparison of sensor data to baseline data is shown in Table 21.

This sensor does not report speed, but does report limited classification data. Additional work to establish a correlation between the Miovision classification scheme and the traditional classification schemes will be done as data analysis continues.

Table 21. Miovision Mainline Freeway Count
12/17/2009

	Baseline (Unverified PLP ADR)	Miovision	Percent Error	Absolute Percent Error
9:00	897*	902	-0.6%	0.6%
9:15	916*	929	1.4%	1.4%
9:30	878	881	0.3%	0.3%
9:45	936	900	-3.8%	3.8%
10:00	792	776	-2.0%	2.0%
10:15	863	847	-1.9%	1.9%
10:30	826	797	-3.5%	3.5%
10:45	897	878	-2.1%	2.1%
11:00	868	846	-2.5%	2.5%
11:15	907	915	0.9%	0.9%
11:30	895	890	-0.6%	0.6%
11:45	958	936	-2.3%	2.3%
12:00	874	847	-3.1%	3.1%
12:15	888	864	-2.7%	2.7%
12:30	881	863	-2.0%	2.0%
12:45	985	956	-2.9%	2.9%
13:00	927	890	-4.0%	4.0%
13:15	1084	1047	-3.4%	3.4%
13:30	979	962	-1.7%	1.7%
TOTAL	**17286**	**16926**	**-2.1%**	**2.2%**

** The PLP ADR baseline was verified from 9:00-9:30.*

Miovision – Turning Movement Counts

Two turning movement counts were conducted. One was conducted at the intersection of an arterial roadway with a collector roadway (TH 7 at Louisiana Ave). The other location was the intersection of two low volume local roads (Lake St. at Water St.). Both tests were done during the evening peak hour (4-6 pm). The results were very accurate. For the high volume intersection, each movement was within two vehicles of the manually counted video baseline. The movements ranged in volume from about 30 to about 320 per 15 minute period. The total percent error per movement throughout the two hour test period was no more than 0.5 % error and the error was most often close to zero.

On the low-volume intersection, errors were similarly small, although due to the low volume, percent errors were higher. Some of these errors could be attributed to manual error. This period was not recounted to verify that the original manual count was accurate. It is also possible that some vehicle movements were counted on an adjacent time period, causing an error. Further investigation will be done into this data, but the sensor generally reported accurate data. A complete table of results is available in Appendix A in Tables A6 and A7.

Aerial images of the two intersections are shown in Figures 32 and 33.

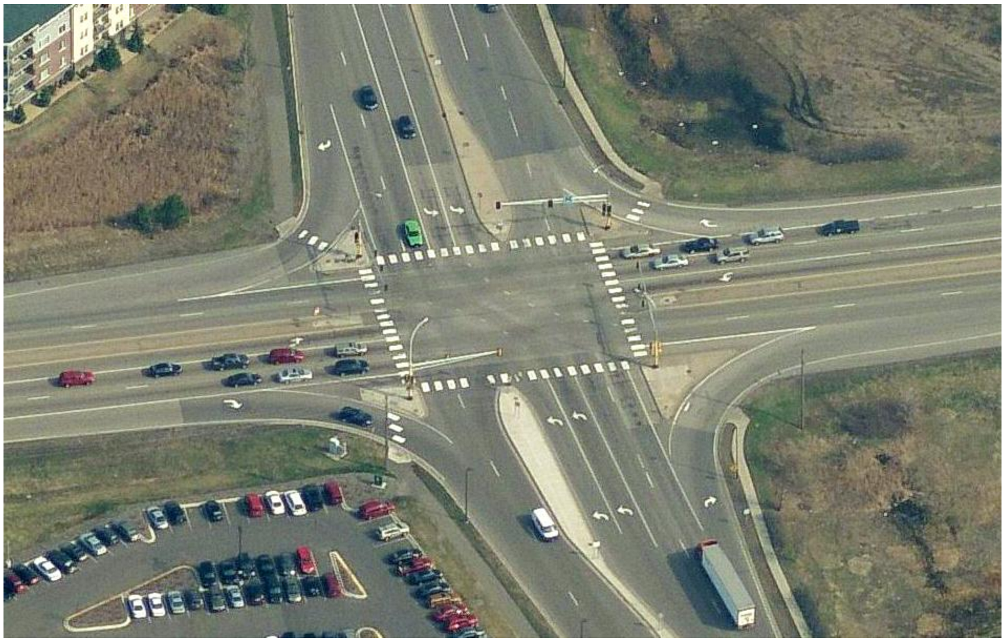


Figure 32. Aerial view, TH 7 and Louisiana Ave, St. Louis Park, MN

Figure 33. Lake and Water St, Excelsior, MN

Miovision – Performance in Various Weather and Lighting Conditions

Only limited data processing time was available, so efforts to test the Miovision sensor were limited to testing under cold weather conditions. The sensor performance was not affected, although sensor setup was much more difficult because much of the fine tuning setup is easiest done with no gloves on. However, setup was fast enough that it could be done in almost any weather condition.

Because the sensor records video, it is important that the camera can view the traffic lanes. In nighttime or low-light conditions, external lighting, such as roadway lighting, must be available so that the sensor can record video. The sensor has excellent automatic lighting adjustments. A few recording sessions were made at the peak hour when lighting conditions changed from daylight to low or no natural light. The sensor continually adjusted for the lighting conditions.

Due to the use of the provided pole-mounted system, it was observed that most available locations for mounting the sensor were on lighting structures. Other possible places (that are recommended to be avoided) were power poles, however these locations should be avoided (or the camera should be positioned) so that the video will not be degraded if the light turns on. Traffic signal poles are good mounting locations as long as the lighting does not degrade the video.

Some wind was observed during testing, but it was not significant enough to cause the telescoping mast to sway enough to cause degraded performance. Some vibration due to wind is acceptable and the video processing can handle it.

Miovision – Installation Findings

The Miovision system that was provided consisted of a telescoping mast with a camera, a pole mounting system, a video collection unit (VCU) and associated accessories. The VCU is internally powered and has all the control and video recording functions on board. The other components are used to mount the camera high up in the air and provide video to the VCU.

The VCU has a slot for a USB flash drive or an SD card for storing the data. The SD Card was used for this project, although the flash drive was used to test that functionality.

The telescoping mast is attached to the pole mount. The pole mount and mast assembly can be mounted on various types of poles or similar structures with tie straps. Rubber pads on the two places the pole mount contacts the pole protect the pole from scratching the pole. However, care must be taken to not scratch a painted pole with the tie strap clasp. Images of the pole mount system being installed are shown in Figure 34.

Figure 34. Miovision Setup at NIT Test Site (Railing Mount)

The physical setup of the sensor is relatively easy with some practice. It is easy to elevate the camera into position once the pole mount is securely mounted to the pole. Rotating the camera into place is easy to do and the camera view can be seen on the VCU. It is important to adjust the camera so that it can see all relevant lanes. On a large intersection, this can be difficult. For example, on the turning movement count at TH 7 and Louisiana Ave, Miovision recommended that two units be used to cover all movements. Because only one unit was available for this test, the sensor was set up to collect as many movements as possible and was able to observe ten of twelve movements.

Figure 35. Miovision VCU with Video Display

One issue was found early on in the use of the sensor. When taking the sensor down, one of the top telescoping sections of the mast fell into the mast assembly. It was retrieved, but was not able to be fully deployed after that issue. It is expected that this type of damage would be repaired on a rental unit.

<u>Miovision – Operational Findings</u>

The main operational difference between Miovision and most other sensors is that users must pay Miovision per hour for data processing. Unlike most sensors, Miovision requires that users send data to them by uploading the video to their trafficdataonline.com website. Users pay a per-hour fee based on how much video is analyzed. The rental prices for the hardware are relatively low, presumably to encourage rental.

The sensor records video to a proprietary format that cannot be viewed without sending the video to Miovision. Miovision provides a few value-added features with their website, such as hosting the video as part of the data analysis for one year. Subsequent hosting can be purchased in addition. A screenshot of the uncompressed video is shown in Figure 33 (top left). A screenshot of the recompressed video that can be downloaded after processing is shown in the image in the top right corner of this figure. An image of the recompressed nighttime video is shown in the bottom left of the figure.

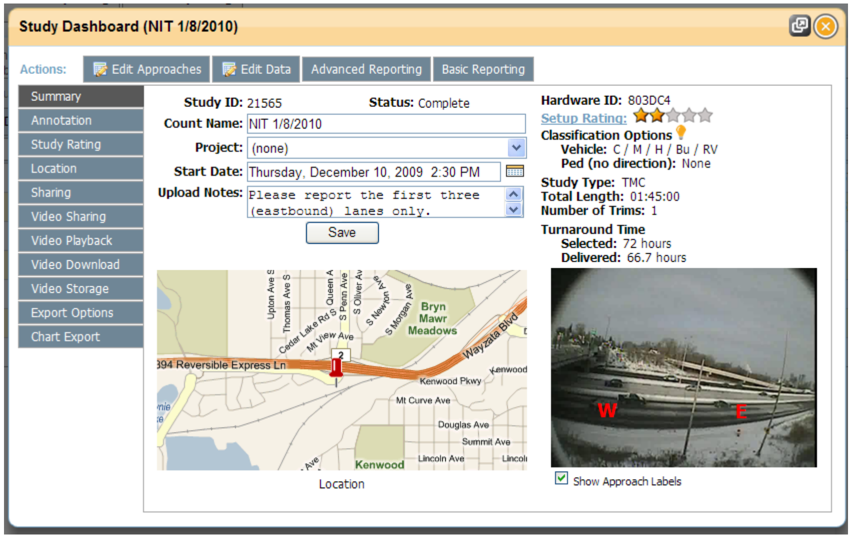
Also, the website organizes and stores the traffic data and supports downloading in a variety of standard formats. Miovision gives a rating to each installation. In Figure 37 (top), the sensor was mounted far from the roadway and Miovision gave the feedback that the sensor should be mounted within 20 feet of the roadway. As shown the bottom images of Figure 37, the setup on the lighting pole near the roadway was given a perfect score.

Daytime, High Resolution

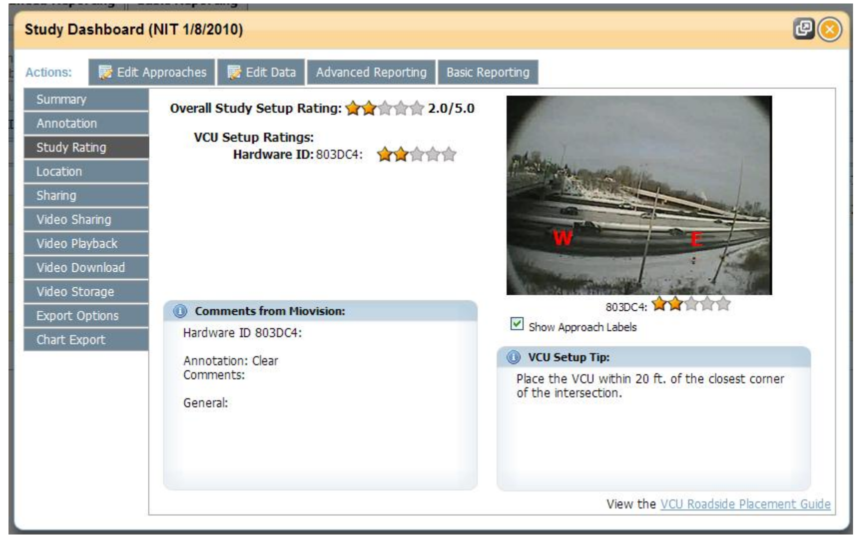
Daytime, Downloadable Resolution

Nighttime, Downloadable Resolution

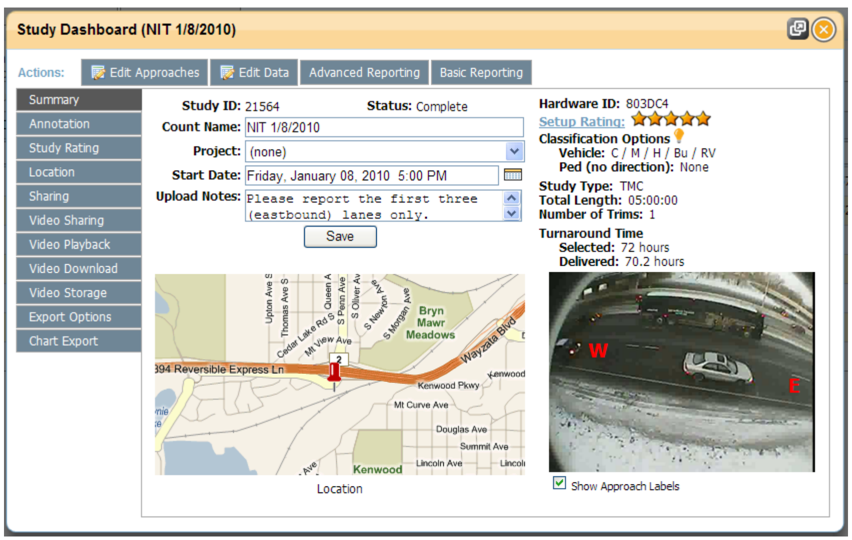
Figure 36. Miovision Screenshots



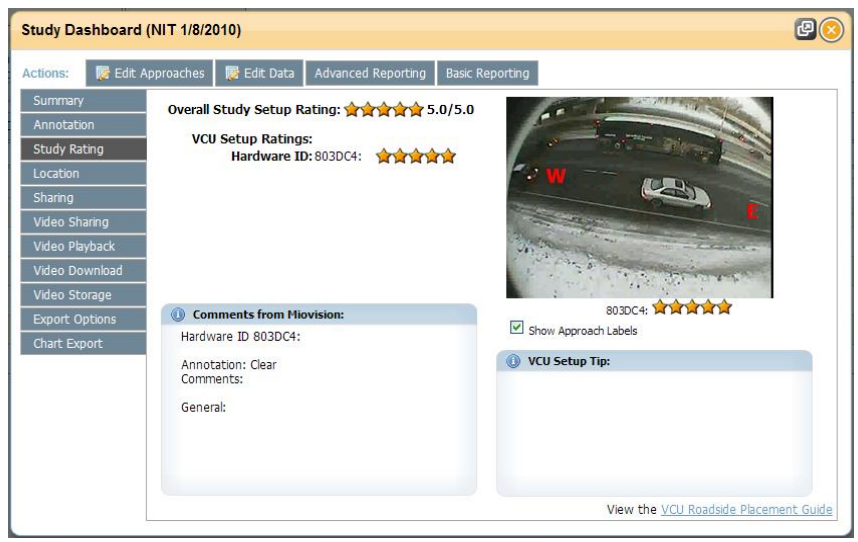
Online Interface - Setup on railing at NIT Test Site



Setup Evaluation - Railing-Mount Setup Evaluation (Two Stars)



Online Interface - Setup on Lighting Pole Near Roadway



Setup Evaluation - Pole-Mount Setup Evaluation (Five Stars)

Figure 37. Miovision Online Interface and Setup Evaluation

Miovision – Maintenance Findings

At the moment, most use of the Miovision system is done through rentals. Thus, maintenance is performed by Miovision. Throughout the testing process, Miovision released update firmware that improved some VCU functions. It is expected that that level of support would continue and firmware could be upgraded periodically.

One maintenance issue was encountered when the VCU's internal battery no longer powered the device and the device could not be charged without turning on. Miovision was responsive in providing support and suggested that the battery be disconnected by removing the top panel of the VCU. This fix reset the VCU and allowed it to boot and then recharge the battery.

Miovision – Cost

The sensor cost is $2,950 for a pole-mount VCU. This includes the camera, mounting hardware, telescoping mast and a 180 day warranty. There is also a cost for the video analysis service which is charged per video hour uploaded with a one-time setup charge of $749 per account. Miovision offers volume pricing of $15 to 22.50 per hour. Online video storage is $5 per 12 hours of video stored per year.

5. CONCLUSIONS

This project found that the current generation improves upon past sensors by providing a more robust data set beyond volume and speed data. Classification is an important capability that has been added and improved over past models. Along with this new function comes a new set of demands for ensuring that vehicles are detected and classified properly. While the length-based sensors generally provided relatively accurate length data, the axle-based sensors sometimes had issues with classifying trucks due to axle-counting errors.

One such error was due to grouping tailgating passenger vehicles. The project's selected classification scheme sometimes grouped passenger vehicles into four-axle trucks because the axle-based sensors do not have a presence detector. A change to the classification scheme removed much of this error. However, agencies must account for these types of errors and must make the class scheme reflect the traffic flow. Agencies must perform independent analysis of their classification schemes to determine whether they will provide acceptable results without a presence sensor.

For the length-based sensors, there is often not a direct correlation between the length of the vehicle and the FHWA 13 class scheme. For example, passenger vehicles carrying trailers or various sized trucks were sometimes classified incorrectly based on a conversion to the 13-class scheme. In these cases, the technology generally performed its function and provided an accurate length, but a new standard for classifying vehicles based on length should be explored (TPF-5(192) is examining this issue).

6. NEXT STEPS

In the project's closing webinar, several ideas for future detection-related pooled fund studies were discussed with the TAC members. The topics that drew the most interest were:

- Future phases of NIT evaluations that focus on new sensors.
- Development of a vehicle detector test bed that would give an ASTM-validated "seal of approval" to sensors that meet defined performance thresholds.
- Weigh-in-motion accuracy and reliability study.

There was also significant interest in portable WIM, such as could be used to provide 48-hour weigh-in-motion studies at freeway speeds. These sensors would not need to be high accuracy. The TAC members participating in the webinar did not know of a product that met these criteria, so a pooled fund could aid with development of a product or evaluation of a new product that meets this need.

Weigh-in-motion systems on bridges were also discussed as a potential research opportunity. These systems use temporary surface-mounted sensors or a combination of strain gauges, accelerometers and temperature sensors on the bridge superstructure to weigh vehicles.

The focus of the TAC members was on tracking the continuous improvement of detection technologies. The group sees pooled fund research opportunities as an important mechanism for implementing this additional research.

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APPENDIX A

SUPPLEMENTARY TABLES

Table A1. Standard Testing Criteria

The following test criteria were developed for this project and are offered as possible testing standard criteria for subsequent evaluations.

Baseline Data Verification • Baseline classification data was independently manually verified with video review. However, due to the large number of four-tire vehicles in the traffic stream, all four-tire vehicles were compared to traffic recorder logs rather than being independently verified. • The axle-spacing accuracy of the piezo-loop-piezo baseline was verified with three types of probe vehicles: compact car (Class 2), DOT maintenance truck (Class 5), lowboy semi (Class 9).
Volume Data Collection • All records were taken as per-vehicle records, not binned data. This reduced the effect of over and under counting errors cancelling each other out, and allowed determination of the number and type of missed and double-counted vehicles. • Because the NIT Test Site has three lanes which could cause occlusion, an overhead camera was used to verify vehicles that were occluded in the view of the sidefire camera.
Speed Data Collection • Per-vehicle speeds were recorded from piezo-loop-piezo baselines. • Speed accuracy was verified with probe vehicle runs. • Outlier baseline data due to stop-and-go conditions were filtered out.
Classification Data Collection • The LTPP classification scheme was used for classification when possible. • Axle-based sensor evaluation focused on their ability to report the correct number of axles and provide correct axle spacings. The next step, assigning vehicles to classification bins, should be considered separately. • Length-based sensors were evaluated for their ability to report vehicle length. • Length classes were matched with axle-classes to determine whether the length-based classification matched comparable axle-based classes. • Vehicle length was measured using a calibrated high resolution pixel measurement process that was verified with reported probe vehicles measurements.

Table A2 NIT Test Site – Weekday Sample
Volumes by Class (LTPP classification scheme)

Time (15 min interval)	Cl. 1	Cl. 2	Cl. 3	Cl. 4	Cl. 5	Cl. 6	Cl. 7	Cl. 8	Cl. 9	Cl. 10	Cl. 11	Cl. 12	Cl. 13
0:00	0	265	13	0	3	0	0	1	1	0	0	0	0
0:15	0	231	15	2	0	0	0	0	0	0	0	0	0
0:30	0	195	16	2	2	0	0	0	2	0	0	0	0
0:45	0	158	8	0	2	0	0	0	0	0	0	0	0
1:00	0	136	17	0	1	0	0	2	1	0	0	0	0
1:15	0	148	5	0	1	0	0	0	0	0	0	0	0
1:30	0	127	6	0	1	0	0	0	1	0	0	0	0
1:45	0	147	8	0	3	0	0	0	2	0	0	0	0
2:00	0	126	5	0	0	1	0	0	1	0	0	0	0
2:15	0	115	10	0	0	2	0	0	0	0	0	0	0
2:30	0	107	9	0	0	0	0	0	0	0	0	0	0
2:45	0	90	4	0	0	2	0	0	0	0	0	0	0
3:00	0	90	2	2	0	1	0	0	1	0	0	0	0
3:15	0	52	5	0	1	0	0	0	1	0	0	0	0
3:30	0	54	5	0	0	1	0	0	4	0	0	0	0
3:45	0	44	2	0	1	0	0	0	0	1	0	0	0
4:00	0	51	7	0	3	0	0	0	0	0	0	0	0
4:15	0	59	10	0	1	1	0	1	0	0	0	0	0
4:30	0	67	10	0	2	0	0	0	1	0	0	0	0
4:45	0	63	10	0	2	2	0	0	1	0	0	0	0
5:00	0	80	8	0	1	0	0	0	3	0	0	0	0
5:15	0	126	7	0	0	0	0	0	1	0	0	0	0
5:30	0	165	6	0	1	1	0	2	2	0	0	0	0
5:45	0	146	20	0	1	0	0	0	1	0	0	0	0
6:00	0	143	14	0	3	1	0	1	1	0	0	0	0
6:15	0	157	17	0	2	0	0	0	1	0	0	0	0
6:30	0	218	26	0	5	0	0	0	3	0	0	0	0
6:45	0	195	20	0	6	1	0	0	0	0	0	0	0
7:00	0	230	21	0	3	0	0	1	0	0	0	0	0
7:15	0	278	27	0	2	0	0	2	0	0	0	0	0
7:30	0	373	27	0	4	0	0	0	2	0	0	0	0
7:45	0	447	44	0	5	1	0	1	1	0	0	0	0

Table A2 (cont.) NIT Test Site – Weekday Sample Volumes by Class (LTPP classification scheme)

Time (15 min interval)	Cl. 1	Cl. 2	Cl. 3	Cl. 4	Cl. 5	Cl. 6	Cl. 7	Cl. 8	Cl. 9	Cl. 10	Cl. 11	Cl. 12	Cl. 13
8:00	0	465	36	0	1	1	0	2	3	0	0	0	0
8:15	0	471	46	0	3	1	0	0	3	0	0	0	0
8:30	1	468	64	0	5	0	0	1	2	0	0	0	0
8:45	0	561	47	1	2	2	0	1	2	0	0	0	0
9:00	0	571	53	0	5	0	0	2	3	0	0	0	0
9:15	0	530	50	0	2	0	0	1	2	0	0	0	1
9:30	0	543	49	0	2	1	0	0	1	0	0	0	0
9:45	1	580	74	0	3	0	0	1	1	0	0	0	0
10:00	0	538	52	0	3	0	0	1	0	0	0	0	0
10:15	0	577	53	0	4	1	0	0	3	0	0	0	0
10:30	1	640	56	1	0	1	0	0	1	0	0	0	0
10:45	0	647	56	1	7	0	0	2	0	0	0	0	0
11:00	1	653	69	0	4	1	0	4	0	0	0	0	0
11:15	1	751	68	0	4	0	0	0	2	0	0	0	0
11:30	0	705	65	2	5	0	0	0	0	0	0	0	0
11:45	0	758	59	2	3	0	1	2	0	0	0	0	0
12:00	1	788	41	0	6	1	0	2	1	0	0	0	0
12:15	1	740	76	1	5	0	0	3	3	0	0	0	0
12:30	1	753	64	0	4	0	0	3	4	0	0	0	0
12:45	1	779	55	1	4	0	0	5	3	0	0	0	0
13:00	1	789	45	0	5	0	0	1	3	0	0	0	0
13:15	5	788	63	1	9	0	0	3	0	0	0	0	0
13:30	3	793	55	0	5	0	2	5	1	1	0	0	0
13:45	7	725	61	3	6	0	0	3	1	0	0	0	0
14:00	6	741	63	0	3	0	0	1	1	0	0	0	0
14:15	2	778	63	0	3	0	0	3	1	1	0	0	0
14:30	4	797	50	0	9	0	0	3	1	0	0	0	0
14:45	4	752	71	1	3	1	0	7	0	0	0	0	0
15:00	8	818	69	1	4	1	0	2	0	0	0	0	0
15:15	6	891	72	0	5	0	0	2	1	0	0	0	0
15:30	6	852	77	0	1	0	0	2	6	0	0	0	0
15:45	5	742	40	1	2	0	0	3	4	0	0	0	0

Table A2 (cont.) NIT Test Site – Weekday Sample Volumes by Class (LTPP classification scheme)

Time (15 min interval)	Cl. 1	Cl. 2	Cl. 3	Cl. 4	Cl. 5	Cl. 6	Cl. 7	Cl. 8	Cl. 9	Cl. 10	Cl. 11	Cl. 12	Cl. 13
16:00	3	697	46	0	3	0	0	1	2	0	0	0	0
16:15	2	776	53	0	1	0	0	4	3	0	0	0	0
16:30	4	772	50	0	4	0	0	1	1	0	0	0	0
16:45	1	698	57	1	1	0	0	1	1	0	0	0	0
17:00	3	743	65	0	4	0	0	3	0	1	0	0	0
17:15	1	807	34	0	4	0	0	2	1	0	0	0	0
17:30	4	687	44	0	3	1	0	1	3	0	0	0	0
17:45	1	549	36	1	2	0	0	0	1	0	0	0	0
18:00	1	519	37	0	3	0	0	1	0	0	0	0	0
18:15	2	482	34	0	4	1	0	1	0	0	0	0	0
18:30	3	473	35	1	3	0	0	2	3	0	0	0	0
18:45	0	490	34	0	2	1	0	0	3	0	0	0	0
19:00	0	473	31	0	4	1	0	1	3	0	0	0	0
19:15	0	461	42	0	4	0	0	0	1	0	0	0	0
19:30	0	440	45	0	4	0	0	1	2	0	0	0	0
19:45	0	397	23	0	1	0	0	1	2	0	0	0	0
20:00	0	357	35	2	3	0	0	0	1	0	0	0	0
20:15	0	399	29	0	0	0	0	1	1	0	0	0	0
20:30	1	341	30	0	1	0	0	0	1	0	0	0	0
20:45	0	292	21	0	3	0	0	0	0	0	0	0	0
21:00	0	306	23	0	6	1	0	1	1	0	0	0	0
21:15	0	338	17	0	3	0	0	0	2	0	0	0	0
21:30	0	240	12	0	2	0	0	1	1	0	0	0	0
21:45	1	208	27	0	3	0	0	0	4	0	0	0	0
22:00	0	189	20	0	3	0	0	0	0	0	0	0	0
22:15	1	180	12	1	0	0	0	0	1	0	1	0	0
22:30	0	149	6	0	0	1	0	0	0	0	0	0	0
22:45	0	118	8	0	2	0	0	0	2	0	0	0	0
23:00	0	106	10	0	1	0	0	0	0	0	0	0	0
23:15	0	97	9	0	2	0	0	0	3	0	0	0	0
23:30	0	88	6	0	0	0	0	0	1	0	0	0	0
23:45	0	66	5	0	2	0	0	0	2	0	0	0	0

Table A3 TH 52 Test Site – Weekday Sample
Volumes by Class (Mn/DOT classification scheme)

Time (15 min interval)	Cl. 2	Cl. 3	Cl. 4	Cl. 5	Cl. 6	Cl. 7	Cl. 8	Cl. 9	Cl. 10	Cl. 11	Cl. 12	Cl. 13
0:00	119	16	0	3	0	0	2	5	0	1	0	0
0:15	75	9	0	2	1	0	2	2	0	0	0	0
0:30	55	9	0	3	0	0	6	6	0	0	0	0
0:45	72	10	1	2	1	0	4	5	0	0	0	0
1:00	65	7	0	4	0	0	5	5	0	0	0	0
1:15	44	8	0	7	1	0	2	5	0	0	1	0
1:30	51	7	0	2	0	0	1	13	0	0	1	0
1:45	37	7	0	4	0	0	3	7	0	0	0	0
2:00	43	9	1	4	0	0	1	8	0	1	0	0
2:15	46	10	0	2	0	0	2	6	0	0	0	0
2:30	31	6	1	1	0	0	3	10	0	2	0	0
2:45	20	8	0	4	0	0	4	3	1	2	0	0
3:00	33	6	0	2	3	0	3	5	0	0	0	0
3:15	30	13	0	2	0	0	2	9	0	1	0	0
3:30	38	14	0	4	1	0	1	11	0	1	0	0
3:45	33	9	0	4	1	0	3	8	0	2	0	0
4:00	32	11	0	5	1	0	1	10	0	1	0	0
4:15	64	10	0	6	0	0	0	9	1	2	1	0
4:30	70	21	0	4	4	0	2	14	0	0	0	0
4:45	84	28	0	5	3	0	3	10	0	1	0	0
5:00	126	46	0	6	2	0	1	27	1	0	0	0
5:15	196	69	0	12	0	0	1	16	0	1	1	0
5:30	296	94	0	9	5	0	2	22	0	1	0	0
5:45	335	113	0	7	6	1	4	22	0	1	0	0
6:00	402	122	0	15	7	0	3	31	0	0	0	0
6:15	574	214	2	14	11	0	4	27	0	0	0	0
6:30	747	244	0	32	8	0	3	31	3	0	0	0
6:45	747	186	1	16	5	0	2	29	0	0	0	0
7:00	847	200	1	28	9	0	3	30	6	1	0	0
7:15	1061	194	2	24	6	1	3	41	2	1	0	2
7:30	1113	212	4	21	14	4	5	35	5	0	0	2
7:45	1042	190	1	31	9	2	5	34	6	0	1	4

Table A3 (cont.) TH 52 Test Site – Weekday Sample Volumes by Class (Mn/DOT classification scheme)

Time (15 min interval)	Cl. 2	Cl. 3	Cl. 4	Cl. 5	Cl. 6	Cl. 7	Cl. 8	Cl. 9	Cl. 10	Cl. 11	Cl. 12	Cl. 13
8:00	860	178	0	22	5	3	8	38	2	0	0	2
8:15	747	181	2	42	6	1	5	39	1	0	0	2
8:30	686	176	1	36	14	1	4	45	4	0	1	1
8:45	647	164	4	18	7	1	5	32	2	0	0	2
9:00	489	136	2	25	9	3	5	48	3	1	1	3
9:15	504	145	2	26	9	4	7	46	5	1	0	2
9:30	520	153	2	20	11	2	4	38	3	0	0	1
9:45	481	149	2	13	11	1	11	55	6	0	0	2
10:00	451	149	4	24	19	2	1	45	3	0	1	2
10:15	495	138	0	27	11	0	3	38	3	0	0	1
10:30	498	154	1	25	15	1	6	48	2	0	0	0
10:45	487	143	2	19	15	3	6	38	8	0	0	0
11:00	483	144	1	27	8	1	5	38	5	0	0	5
11:15	499	151	1	27	15	2	5	45	4	0	1	0
11:30	555	150	2	30	15	0	3	34	1	0	0	0
11:45	503	144	1	32	12	1	6	37	3	0	0	1
12:00	537	162	1	23	12	2	5	38	3	0	1	3
12:15	532	150	1	28	9	0	6	43	5	0	2	4
12:30	529	181	2	31	15	3	4	35	5	0	0	0
12:45	517	143	4	28	8	2	6	36	5	0	0	3
13:00	533	169	1	34	17	2	3	35	4	0	0	1
13:15	549	157	4	17	10	0	2	41	4	0	0	0
13:30	605	148	0	40	14	3	4	36	6	0	0	2
13:45	544	188	2	34	14	1	7	27	0	0	1	3
14:00	628	196	3	34	9	1	10	26	1	0	1	0
14:15	665	167	1	41	18	0	7	33	6	0	0	1
14:30	658	178	1	25	10	1	4	29	3	0	0	1
14:45	685	193	0	23	6	2	7	45	3	0	0	1
15:00	791	214	3	23	12	0	7	38	2	0	1	3
15:15	810	222	1	31	8	0	6	25	2	0	0	0
15:30	923	250	0	23	16	0	7	25	1	0	0	0
15:45	983	248	2	27	9	0	4	24	1	0	0	1

Table A3 (cont.) TH 52 Test Site – Weekday Sample Volumes by Class (Mn/DOT classification scheme)

Time (15 min interval)	Cl. 2	Cl. 3	Cl. 4	Cl. 5	Cl. 6	Cl. 7	Cl. 8	Cl. 9	Cl. 10	Cl. 11	Cl. 12	Cl. 13
16:00	932	224	0	30	6	0	4	18	1	0	0	0
16:15	1053	226	2	23	4	0	4	21	0	0	0	0
16:30	1146	234	1	16	3	0	7	18	1	0	0	0
16:45	1264	180	2	23	2	0	6	22	0	1	0	0
17:00	1174	213	2	13	2	0	4	18	0	0	0	0
17:15	1082	207	1	12	5	0	5	22	0	0	0	0
17:30	1024	211	1	10	3	1	3	19	0	0	0	0
17:45	918	179	1	19	2	0	4	30	0	0	0	0
18:00	811	152	0	17	1	1	3	19	1	0	0	0
18:15	744	127	0	11	4	0	1	15	1	1	0	0
18:30	656	138	0	10	2	0	4	16	0	0	0	0
18:45	533	109	0	10	0	0	3	14	0	0	0	0
19:00	520	109	0	9	3	0	1	14	0	0	0	0
19:15	553	103	0	8	1	0	1	12	1	1	0	0
19:30	482	95	0	11	1	0	1	7	1	1	0	0
19:45	477	85	0	7	5	0	2	20	0	0	0	0
20:00	468	95	0	4	2	0	0	15	1	0	1	0
20:15	445	81	1	6	0	0	5	12	0	1	0	0
20:30	440	97	0	7	3	0	2	9	0	0	0	0
20:45	406	67	0	7	1	0	1	3	0	1	0	0
21:00	415	70	0	4	1	0	3	6	0	0	1	0
21:15	435	60	1	5	1	0	2	10	0	1	0	0
21:30	359	50	2	4	1	0	4	16	0	1	1	0
21:45	302	63	1	5	4	0	2	9	0	6	1	0
22:00	270	39	0	3	2	1	1	9	1	1	0	0
22:15	242	48	1	6	2	0	4	5	0	1	0	0
22:30	244	33	2	3	2	0	1	10	0	2	0	0
22:45	225	27	0	5	0	0	2	14	0	1	0	0
23:00	195	33	1	7	2	0	1	10	0	0	1	0
23:15	158	22	1	5	0	0	4	8	0	0	0	0
23:30	131	19	0	2	1	0	1	9	0	2	0	0
23:45	136	19	0	1	1	0	3	4	0	2	0	0

Table A4. Wavetronix SmartSensor HD

Lane	Length	Speed	Class	Range	Time	Correct?	Visually Verified Axle-Based Class	Notes
Correct (Large)								
LANE_01	74		4	44	11:44:36	YES	9	
LANE_01	74	53	4	43	11:49:47	YES	9	
LANE_01	76	60.8	4	44	11:39:43	YES	9	
LANE_01	77		4	44	11:42:52	YES	9	
LANE_01	78		4	43	11:48:11	YES	9	
LANE_01	78		4	44	11:52:30	YES	9	
LANE_01	79	62.6	4	48	11:38:40	YES	9	
LANE_01	79	55.8	4	44	11:53:52	YES	9	
LANE_01	82		4	43	11:56:49	YES	9	
LANE_01	83		4	43	11:41:15	YES	9	
LANE_01	83	64	4	48	11:44:13	YES	9	
LANE_01	64	48.9	4	44	11:44:17	YES	9	
LANE_01	64		4	44	12:00:10	YES	9	
LANE_01	68		4	43	11:48:00	YES	9	
LANE_01	69	53.2	4	43	11:37:01	YES	9	
LANE_01	46	66.7	4	43	11:48:59	YES	8	
LANE_01	51	61.4	4	43	11:41:45	YES	8	
LANE_01	57		4	43	11:40:32	YES	9	
LANE_01	57	51.9	4	44	11:40:54	YES	9	
LANE_01	62	46.3	4	44	11:54:01	YES	9	
LANE_02	52	59.3	4	54	11:52:42	YES	10	
LANE_02	59	52.3	4	54	11:34:41	YES	9	
LANE_02	60	54.8	4	54	11:50:46	YES	9	
LANE_02	63	54.3	4	53	11:55:05	YES	9	
LANE_02	72	58.9	4	53	11:44:11	YES	9	
LANE_02	76	65.6	4	52	11:43:43	YES	9	

LANE_03	45	59.5	4	62	11:47:08	YES	8	
LANE_03	47	76.5	4	60	11:54:27	YES	8	
LANE_03	60	62.4	4	64	11:54:53	YES	9	
LANE_03	71	62.6	4	60	11:36:09	YES	8	
						Total	30	
Correct (Small)								
LANE_01	24		3	44	11:40:56	YES	6	
LANE_01	29		3	44	11:43:59	YES	6	
LANE_01	30	58.5	3	44	11:50:35	YES	6	
LANE_01	31		3	43	11:47:14	YES	6	
LANE_01	38	62	3	44	11:36:42	YES	6	
LANE_01	25	53	3	44	11:42:49	YES	5	
LANE_02	23	57.7	3	54	11:53:39	YES	5	
LANE_02	23	62.1	3	54	12:00:36	YES	5	
LANE_02	24		3	54	11:35:49	YES	5	
LANE_02	25	59.1	3	54	11:57:10	YES	5	
LANE_02	26	59.3	3	50	11:35:42	YES	5	
LANE_02	27	64.7	3	54	11:52:59	YES	5	
LANE_02	29	54	3	52	11:52:43	YES	6	
LANE_02	29		3	54	12:00:16	YES	6	
LANE_02	33	61.8	3	53	11:45:19	YES	5	
LANE_02	34	59.2	3	54	11:40:31	YES	5	
LANE_02	34	54.3	3	52	11:50:24	YES	5	
LANE_02	34	63.5	3	54	11:56:14	YES	6	
LANE_02	39	52.4	3	54	11:51:46	YES	5	
LANE_02	30		3	53	11:51:33	YES	5	
LANE_03	28	61.3	3	64	11:50:40	YES	5	
LANE_03	29	60.6	3	62	11:51:48	YES	5	
LANE_03	29	67.2	3	64	11:52:14	YES	5	
LANE_03	32	67.9	3	62	11:40:36	YES	5	
LANE_03	35	61.8	3	64	11:47:37	YES	5	
LANE_03	27	62.9	3	63	11:59:22	YES	5	
LANE_03	24	69.7	3	62	11:38:21	YES	5	

LANE_03	24	65.3	3	64	11:51:55	YES	5	
LANE_03	40	63.3	4	64	11:47:12	YES	5	
LANE_03	23	64	3	62	11:42:25	YES	5	Small Tow Truck - metal hanging off back?
LANE_03	24	64.7	3	62	11:46:54	YES	4	Short Bus
						Total	31	
Undetected Trucks (Large)								
LANE_03	20	64.1	2	62	11:45:41	NO	5	Small SU Truck
LANE_02	20	65.8	2	53	11:42:05	NO	5	Small SU Truck
LANE_02	22	55.8	3	52	11:55:32	NO	5	SU Truck
						Total	3	
Misclassified Trucks (small classified as large)								
LANE_02	42		4	52	11:56:19	NO	5	SU Truck
LANE_02	109	62.5	4	52	11:48:00	NO	6	SU truck, bleed from Lane 1
LANE_02	49	58.2	4	52	11:44:55	NO	5	SU Truck with trailer
LANE_02	41	63.7	4	52	12:00:00	NO	6	Garbage truck, extended back
LANE_02	41	54.8	4	54	11:44:44	NO	5	Small truck with trailer
LANE_02	41	52.6	4	52	11:54:50	NO	5	SU Truck with extended back end
LANE_01	45	62.9	4	44	11:53:29	NO	6	Short tank truck, multiple veh bleed?
LANE_01	45	65.6	4	43	11:54:40	NO	5	SU Truck
LANE_01	73	64.8	4	44	11:40:46	NO	6	Class 6 truck pulling trailer
LANE_01	42	65.2	4	44	11:39:07	NO	5	SU Truck
LANE_02	44	62.7	4	54	11:36:42	NO	5	SU Truck, car bleeding from Lane 2?
						Count	11	

Non-trucks classified as trucks								
LANE_01	23	59.7	3	44	11:34:10	NO	3	Pickup
LANE_01	23	64.5	3	44	11:34:55	NO	3	Pickup
LANE_01	23	77.5	3	44	11:35:53	NO	3	Pickup
LANE_01	23	66	3	44	11:36:10	NO	3	Pickup
LANE_01	23	71	3	44	11:38:33	NO	3	Pickup
LANE_01	23	63.3	3	46	11:46:05	NO	3	SUV

LANE_01	23		3	44	11:52:25	NO	3	Pickup
LANE_01	23	64.5	3	44	11:53:12	NO	3	Pickup
LANE_01	23		3	44	11:53:17	NO	3	Van
LANE_01	23		3	44	11:56:47	NO	3	Van
LANE_01	24		3	44	11:40:19	NO	3	SUV
LANE_01	25		3	44	11:54:49	NO	3	Pickup
LANE_01	27		3	36	11:49:47	NO	N/A	Double Count Class 9
LANE_01	28		3	44	11:55:04	NO	3	Minivan
LANE_01	42	65.8	4	42	11:43:43	NO	2	Bleed from Lane 2
LANE_02	26	67.3	3	53	11:48:59	NO	N/A	Truck from Lane 1 bleeding over to Lane 2
LANE_02	26	66.1	3	54	12:01:25	NO	3	Pickup in Lane 1, moving to Lane 2, or SUV in Lane 2, possible blending
LANE_02	32	61.4	3	54	11:46:23	NO	3	Van with trailer
LANE_02	34	60.3	3	54	11:36:24	NO	3	Pickup with large mesh rack in Lane 1
LANE_02	42	57.5	4	54	11:42:43	NO	3	Pickup with trailer
LANE_02	50	57.7	4	49	11:51:27	NO	2	Two PCs bleeding together
LANE_02	58		4	51	11:53:53	NO	N/A	Bleed over from Lane 1
LANE_02	85	50.8	4	52	11:49:47	NO	N/A	Bleed over from Lane 1, leading car in lane 2
LANE_03	23	72.7	3	64	11:53:24	NO	3	Pickup
LANE_03	24	62.3	3	63	11:38:17	NO	3	SUV, multiple cars arrive at once
LANE_03	25	64.3	3	64	11:36:49	NO	2	Small SUV, Multiple cars arriving at once
LANE_03	28	66.8	3	64	11:35:22	NO	3	Pickup
LANE_03	41	66.6	4	64	11:38:06	NO	3	Pickup with trailer
LANE_03	44	59.5	4	64	11:47:17	NO	N/A	SUV, multiple vehicles bleeding together
LANE_03	50	65.6	4	64	11:35:02	NO	3	Pickup with trailer
						Total	30	

Table A5. GTT Microloops

Lane	Length	Speed	Class	Range	Date	Time	Correct?	Visually Verified Axle-Based Class	Pic #	Notes
Correct (large)										
1	66	53	N/A	N/A	1/20/2010	11:37:01 AM	YES	9	19	Correct
1	71	60	N/A	N/A	1/20/2010	11:38:40 AM	YES	9	21	Correct
1	64	60	N/A	N/A	1/20/2010	11:39:44 AM	YES	9	25	Correct
1	64	60	N/A	N/A	1/20/2010	11:40:33 AM	YES	9	27	Correct
1	78	60	N/A	N/A	1/20/2010	11:41:16 AM	YES	9	31	Correct
1	49	57	N/A	N/A	1/20/2010	11:41:45 AM	YES	8	33	Correct
1	54	48	N/A	N/A	1/20/2010	11:42:53 AM	YES	9	38	Correct
1	40	42	N/A	N/A	1/20/2010	11:44:14 AM	YES	9	128	Correct
1	71	53	N/A	N/A	1/20/2010	11:44:18 AM	YES	9	42	Correct
1	53	43	N/A	N/A	1/20/2010	11:44:36 AM	YES	9	43	Correct
1	74	55	N/A	N/A	1/20/2010	11:48:12 AM	YES	9	56	Correct
1	40	61	N/A	N/A	1/20/2010	11:49:00 AM	YES	8	58	Correct
1	74	53	N/A	N/A	1/20/2010	11:49:48 AM	YES	9	61	Correct
1	77	55	N/A	N/A	1/20/2010	11:52:31 AM	YES	9	71	Correct
1	82	57	N/A	N/A	1/20/2010	11:53:53 AM	YES	9	77	Correct
1	71	55	N/A	N/A	1/20/2010	11:54:02 AM	YES	9	129	Correct
1	60	52	N/A	N/A	1/20/2010	11:56:50 AM	YES	9	87	Correct
2	52	57	N/A	N/A	1/20/2010	11:34:42 AM	YES	9	14	Correct
2	70	60	N/A	N/A	1/20/2010	11:43:44 AM	YES	9	39	Correct
2	55	62	N/A	N/A	1/20/2010	11:44:11 AM	YES	9	41	Correct
2	58	55	N/A	N/A	1/20/2010	11:50:47 AM	YES	9	65	Correct
2	43	60	N/A	N/A	1/20/2010	11:52:42 AM	YES	10	72	Correct
2	58	52	N/A	N/A	1/20/2010	11:55:06 AM	YES	9	82	Correct
3	46	60	N/A	N/A	1/20/2010	11:47:10 AM	YES	8	49	Correct
3	47	65	N/A	N/A	1/20/2010	11:54:55 AM	YES	9	81	Correct
Correct (small)										

1	36	60	N/A	N/A	1/20/2010	11:35:33 AM	YES	5	16	Correct
1	38	61	N/A	N/A	1/20/2010	11:36:42 AM	YES	6	18	Correct
1	29	60	N/A	N/A	1/20/2010	11:38:59 AM	YES	5	22	Correct
1	24	55	N/A	N/A	1/20/2010	11:39:05 AM	YES	5	23	Correct
1	27	55	N/A	N/A	1/20/2010	11:40:57 AM	YES	5	30	Correct
1	28	60	N/A	N/A	1/20/2010	11:41:25 AM	YES	5	114	Correct
1	33	57	N/A	N/A	1/20/2010	11:41:43 AM	YES	5	32	Correct
1	24	55	N/A	N/A	1/20/2010	11:42:35 AM	YES	5	36	Correct
1	28	53	N/A	N/A	1/20/2010	11:42:50 AM	YES	5	164	Correct
1	33	60	N/A	N/A	1/20/2010	11:44:00 AM	YES	6	40	Correct
1	26	55	N/A	N/A	1/20/2010	11:46:05 AM	YES	5	47	Correct
1	30	52	N/A	N/A	1/20/2010	11:47:15 AM	YES	6	51	Correct
1	27	53	N/A	N/A	1/20/2010	11:48:05 AM	YES	5	55	Correct
1	23	55	N/A	N/A	1/20/2010	11:48:48 AM	YES	5	57	Correct
1	23	57	N/A	N/A	1/20/2010	11:48:53 AM	YES	5	171	Correct
1	33	53	N/A	N/A	1/20/2010	11:49:44 AM	YES	5	60	Correct
1	34	60	N/A	N/A	1/20/2010	11:57:51 AM	YES	5	89	Correct
1	33	60	N/A	N/A	1/20/2010	11:57:57 AM	YES	4	90	Correct
1	37	55	N/A	N/A	1/20/2010	11:58:28 AM	YES	5	91	Correct
2	28	60	N/A	N/A	1/20/2010	11:40:31 AM	YES	5	26	Correct
2	28	55	N/A	N/A	1/20/2010	11:45:20 AM	YES	5	46	Correct
2	33	55	N/A	N/A	1/20/2010	11:50:25 AM	YES	5	62	Correct
2	28	62	N/A	N/A	1/20/2010	11:51:33 AM	YES	5	148	Correct
2	31	57	N/A	N/A	1/20/2010	11:52:44 AM	YES	6	73	Correct
2	26	60	N/A	N/A	1/20/2010	11:52:59 AM	YES	5	74	Correct
2	26	61	N/A	N/A	1/20/2010	11:55:32 AM	YES	5	83	Correct
2	37	62	N/A	N/A	1/20/2010	11:56:14 AM	YES	6	85	Correct
2	33	57	N/A	N/A	1/20/2010	11:56:19 AM	YES	5	86	Correct
3	30	65	N/A	N/A	1/20/2010	11:40:38 AM	YES	5	113	Correct
3	32	60	N/A	N/A	1/20/2010	11:47:14 AM	YES	5	50	Correct
3	34	62	N/A	N/A	1/20/2010	11:47:39 AM	YES	5	52	Correct
3	33	55	N/A	N/A	1/20/2010	11:50:42 AM	YES	5	64	Correct
3	24	65	N/A	N/A	1/20/2010	11:52:16 AM	YES	5	70	Correct

3	24	62	N/A	N/A	1/20/2010	11:59:24 AM	YES	5	92	Correct
Undetected Trucks (Large)										
3					1/20/2010	11:36:10	NO	8	17	
Undetected Trucks (Small)										
1	5	51	N/A	N/A	1/20/2010	11:35:42 AM	NO	5	108	Double Count, Lane change
1					1/20/2011	11:39:08	NO	5	24	SU Truck
1	9	55	N/A	N/A	1/20/2010	11:39:55 AM	NO	5	112	SU Truck
1	20	60	N/A	N/A	1/20/2010	11:49:04 AM	NO	5	59	SU Truck
1	20	48	N/A	N/A	1/20/2010	11:50:36 AM	NO	6	63	SU Truck, 3 axles
1	16	55	N/A	N/A	1/20/2010	11:51:03 AM	NO	5	66	SU Truck
1	20	51	N/A	N/A	1/20/2010	11:53:30 AM	NO	6	76	SU Truck, tank
1	18	55	N/A	N/A	1/20/2010	11:54:40 AM	NO	5	79	SU Truck
1	15	60	N/A	N/A	1/20/2010	11:55:37 AM	NO	5	84	SU Truck
2					1/20/2010	11:35:50	NO	5	109	SU Truck
2					1/20/2010	11:42:05	NO	5	34	Small SU Truck
2					1/20/2010	11:51:47	NO	5	67	SU Truck
2					1/20/2010	11:57:11	NO	5	88	SU Truck
3					1/20/2010	11:46:54	NO	4	145	Short Bus
3					1/20/2010	11:51:49	NO	5	68	SU Truck
3					1/20/2010	11:51:56	NO	5	69	Long Delivery Van
3					1/20/2010	11:53:27	NO	4	75	Short Bus
3					1/20/2010	11:42:25	NO	5	140	Short tow truck
Misclassified Trucks (large classified as small)										
1	30	55	N/A	N/A	1/20/2010	11:40:55 AM	NO	9	29	Class 9 truck
1	30	34	N/A	N/A	1/20/2010	11:48:01 AM	NO	9	54	Class 9 Truck
Misclassified Trucks (small classified as large)										
1	54	55	N/A	N/A	1/20/2010	11:40:47 AM	NO	6	28	Class 6 Truck pulling a trailer
2	44	55	N/A	N/A	1/20/2010	11:44:55 AM	NO	5	45	Class 5 Pulling trailer
2	49	61	N/A	N/A	1/20/2010	11:48:00 AM	NO	6	53	Class 6 Truck
2	42	55	N/A	N/A	1/20/2010	11:54:51 AM	NO	5	80	SU Truck with extended back end

2	43	60	N/A	N/A	1/20/2010	12:00:00 PM	NO	6	93	SU Truck with extended back end
Non-trucks classified as trucks										
1	23	55	N/A	N/A	1/20/2010	11:54:03 AM	NO	3	178	Class 3 with plow
2	23	53	N/A	N/A	1/20/2010	11:49:42 AM	NO	3	172	Long Van
2	23	62	N/A	N/A	1/20/2010	11:50:34 AM	NO	3	173	Van, Should be Class 3
3	23	71	N/A	N/A	1/20/2010	11:42:13 AM	NO	3	184	Pickup Truck
3	23	71	N/A	N/A	1/20/2010	11:57:15 AM	NO	2	179	Passenger car
1	24	65	N/A	N/A	1/20/2010	11:39:41 AM	NO	3	183	Pickup Truck
1	26	78	N/A	N/A	1/20/2010	11:34:35 AM	NO	3	107	Long Pickup - Should be 3
2	26	68	N/A	N/A	1/20/2010	11:46:24 AM	NO	3	48	Class 3 Pulling trailer
2	26	123	N/A	N/A	1/20/2010	11:58:23 AM	NO	2	180	Lane change?
3	26	46	N/A	N/A	1/20/2010	11:42:24 AM	NO	2	170	Passenger car
1	32	55	N/A	N/A	1/20/2010	11:53:57 AM	NO	2	177	Lane Change?
3	32	60	N/A	N/A	1/20/2010	11:45:21 AM	NO	N/A	46	Interference from Lane 2?
3	33	68	N/A	N/A	1/20/2010	11:38:08 AM	NO	3	130	Class 3 Pulling trailer
1	35	53	N/A	N/A	1/20/2010	11:53:46 AM	NO	2	126	Passenger Cars, lane change
2	35	53	N/A	N/A	1/20/2010	11:44:45 AM	NO	3	44	Class 3 Pulling trailer
2	36	65	N/A	N/A	1/20/2010	11:54:01 AM	NO	2	129	Disturbance from lane 1?
2	39	55	N/A	N/A	1/20/2010	11:42:44 AM	NO	3	37	Class 3 Pulling trailer
3	39	68	N/A	N/A	1/20/2010	11:54:29 AM	NO	3	127	Long Pickup with trailer
2	45	62	N/A	N/A	1/20/2010	11:37:32 AM	NO	?	182	2 Cars Tailgating - Lane Change
1	48	55	N/A	N/A	1/20/2010	11:51:28 AM	NO	2	125,134	Passenger Cars, lane change
1	56	57	N/A	N/A	1/20/2010	11:50:51 AM	NO	?	174	Tailgating?
1	58	62	N/A	N/A	1/20/2010	11:52:57 AM	NO	2	176	Passenger Cars, lane change
3	71	75	N/A	N/A	1/20/2010	11:35:43 AM	NO	N/A	169	No car in this lane

Table A6. Miovision Turning Movement Count Results (High Volume Intersection)

Miovision Turning Movement Count
TH 7 at Louisiana Ave
1/11/2010, 4:00-6:00 pm

Southbound

	Manual				Sensor				Percent Error			
Start Time	Right	Thru	Left	U-Turn	Right	Thru	Left	U-Turn	Right	Thru	Left	U-Turn
4:00 PM	30	39	32	0	31	39	33	0	-3.3	0.0	-3.1	0.0
4:15 PM	34	48	23	0	35	48	22	0	-2.9	0.0	4.3	0.0
4:30 PM	31	40	24	2	30	40	24	2	3.2	0.0	0.0	0.0
4:45 PM	35	48	37	0	35	48	37	0	0.0	0.0	0.0	0.0
5:00 PM	49	49	48	0	50	49	48	0	-2.0	0.0	0.0	0.0
5:15 PM	44	47	27	0	44	47	26	0	0.0	0.0	3.7	0.0
5:30 PM	43	47	35	0	43	48	35	0	0.0	-2.1	0.0	0.0
5:45 PM	39	39	34	0	38	39	34	0	2.6	0.0	0.0	0.0
TOTALS	305	357	260	2	306	358	259	2	0.3	0.3	0.4	0.0

Westbound

	Manual				Sensor				Percent Error			
Start Time	Right	Thru	Left	U-Turn	Right	Thru	Left	U-Turn	Right	Thru	Left	U-Turn
4:00 PM	17	169	39	3	17	170	39	3	0.0	0.6	0.0	0.0
4:15 PM	12	210	33	3	13	210	33	3	8.3	0.0	0.0	0.0
4:30 PM	19	250	31	3	18	250	32	3	5.3	0.0	3.2	0.0
4:45 PM	20	239	37	5	20	239	36	5	0.0	0.0	2.7	0.0
5:00 PM	25	223	22	5	25	223	22	5	0.0	0.0	0.0	0.0
5:15 PM	30	254	31	6	30	254	31	6	0.0	0.0	0.0	0.0
5:30 PM	24	278	41	5	24	278	41	5	0.0	0.0	0.0	0.0
5:45 PM	26	220	38	6	25	220	38	6	3.8	0.0	0.0	0.0
TOTALS	173	1843	272	36	172	1844	272	36	0.6	0.1	0.0	0.0

Northbound

	Manual				Sensor				Percent Error			
Start Time	Right	Thru	Left	U-Turn	Right	Thru	Left	U-Turn	Right	Thru	Left	U-Turn
4:00 PM	N/A	100	114	0	N/A	100	114	0	N/A	0.0	0.0	0.0
4:15 PM	N/A	72	93	0	N/A	73	92	0	N/A	1.4	1.1	0.0
4:30 PM	N/A	110	86	0	N/A	110	86	0	N/A	0.0	0.0	0.0
4:45 PM	N/A	91	113	0	N/A	91	112	0	N/A	0.0	0.9	0.0
5:00 PM	N/A	95	99	0	N/A	94	100	0	N/A	1.1	1.0	0.0
5:15 PM	N/A	110	93	0	N/A	110	93	0	N/A	0.0	0.0	0.0
5:30 PM	N/A	88	81	0	N/A	88	81	0	N/A	0.0	0.0	0.0
5:45 PM	N/A	76	72	1	N/A	76	72	1	N/A	0.0	0.0	0.0
TOTALS	0	742	751	1	0	742	750	1	N/A	0.0	0.1	0.0

Eastbound

	Manual				Sensor				Percent Error			
Start Time	Right	Thru	Left	U-Turn	Right	Thru	Left	U-Turn	Right	Thru	Left	U-Turn
4:00 PM	N/A	191	41	1	N/A	190	42	1	N/A	0.5	2.4	0.0
4:15 PM	N/A	241	59	1	N/A	241	59	1	N/A	0.0	0.0	0.0
4:30 PM	N/A	274	44	0	N/A	274	44	0	N/A	0.0	0.0	0.0
4:45 PM	N/A	286	56	0	N/A	285	57	0	N/A	0.3	1.8	0.0
5:00 PM	N/A	319	66	0	N/A	319	66	0	N/A	0.0	0.0	0.0
5:15 PM	N/A	314	70	1	N/A	312	70	1	N/A	0.6	0.0	0.0
5:30 PM	N/A	260	60	0	N/A	260	59	0	N/A	0.0	1.7	0.0
5:45 PM	N/A	235	37	0	N/A	235	38	0	N/A	0.0	2.7	0.0
TOTALS	0	2120	433	3	0	2116	435	3	N/A	0.2	0.5	0.0

Table A7. Miovision Turning Movement Count Results (Low Volume Intersection)

Miovision Turning Movement Count
Lake St, Water St, Excelsior, MN
12/2/2009, 4:00-6:00 pm

Southbound

	Baseline (Manual Count)			Sensor			Percent Error		
Start Time	Right	Thru	Left	Right	Thru	Left	Right	Thru	Left
4:00 PM	0	0	0	0	0	0	0%	0%	0%
4:15 PM	0	0	0	0	0	0	0%	0%	0%
4:30 PM	0	0	0	0	0	0	0%	0%	0%
4:45 PM	0	0	0	0	0	0	0%	0%	0%
5:00 PM	0	0	0	0	0	0	0%	0%	0%
5:15 PM	0	0	0	0	0	0	0%	0%	0%
5:30 PM	0	0	0	0	0	0	0%	0%	0%
5:45 PM	0	0	0	0	0	0	0%	0%	0%
TOTALS	0	0	0	0	0	0	0%	0%	0%

Westbound

	Baseline (Manual Count)			Sensor			Percent Error		
Start Time	Right	Thru	Left	Right	Thru	Left	Right	Thru	Left
4:00 PM	0	5	15	0	5	15	0%	0%	0%
4:15 PM	0	7	16	0	7	14	0%	0%	-13%
4:30 PM	0	5	8	0	5	9	0%	0%	13%
4:45 PM	1	4	16	0	5	16	-100%	25%	0%
5:00 PM	0	6	15	0	6	15	0%	0%	0%
5:15 PM	0	4	12	0	4	11	0%	0%	-8%
5:30 PM	0	5	7	0	5	8	0%	0%	14%
5:45 PM	1	6	5	0	5	4	-100%	-17%	-20%
TOTALS	2	42	94	0	42	92	-100%	0%	-2%

Northbound

	Baseline (Manual Count)			Sensor			Percent Error		
Start Time	Right	Thru	Left	Right	Thru	Left	Right	Thru	Left
4:00 PM	6	0	7	6	0	5	0%	0%	-29%
4:15 PM	13	0	2	13	0	4	0%	0%	100%
4:30 PM	17	0	7	15	0	7	-12%	0%	0%
4:45 PM	12	0	2	13	0	2	8%	0%	0%
5:00 PM	9	0	5	9	0	4	0%	0%	-20%
5:15 PM	8	0	0	9	0	1	13%	0%	0%
5:30 PM	2	0	2	2	0	3	0%	0%	50%
5:45 PM	5	0	1	5	0	1	0%	0%	0%
TOTALS	72	0	26	72	0	27	0%	0%	4%

Eastbound

	Baseline (Manual Count)			Sensor			Percent Error		
Start Time	Right	Thru	Left	Right	Thru	Left	Right	Thru	Left
4:00 PM	4	3	0	2	2	0	-50%	-33%	0%
4:15 PM	3	1	0	5	2	0	67%	100%	0%
4:30 PM	3	5	0	3	4	0	0%	-20%	0%
4:45 PM	2	6	0	2	6	0	0%	0%	0%
5:00 PM	3	3	0	3	4	0	0%	33%	0%
5:15 PM	2	5	0	2	6	0	0%	20%	0%
5:30 PM	1	8	0	1	8	0	0%	0%	0%
5:45 PM	0	4	0	0	5	0	0%	25%	0%
TOTALS	18	35	0	18	37	0	0%	6%	0%