Accuracy, Consistency, and Reliability of Raw Traffic Data from Vehicle Detection Systems, Phase II
BDV28-977-08

Final Report

October, 2018

Presented by:
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Disclaimer

"The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation."

Unit Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F

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16. Abstract

With an ever-increasing vehicle population, transportation agencies face many challenges to maintain acceptable levels of mobility while maximizing roadway safety. Traffic management centers (TMCs) are implementing active management strategies such as express lanes, ramp metering, and running shoulder as well as the traditional intelligent transportation systems (ITS) functions such as incident detection and traffic monitoring. These applications rely on a network of roadway sensors to ensure that the control strategy matches the current traffic conditions. This work focused on data accuracy and maintenance of microwave vehicle detection systems (MVDSs), impact on the TMC applications, testing, and maintenance strategies. First, a literature review of the accuracy requirements for MVDSs in different agencies in the U.S was conducted. Interviews with staff in several Florida Department of Transportation (FDOT) districts were conducted to determine failure modes, data, and maintenance issues faced with respect to MVDSs. Field data was collected and analyzed to produce an assessment of the variation of MVDSs accuracy over time. Recommendations for acceptance testing, inspection, and accuracy monitoring are provided in the report.

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Executive Summary

Introduction

With an ever-increasing vehicle population, transportation agencies face many challenges to maintain acceptable levels of mobility while maximizing roadway safety. Traffic management centers (TMCs) are implementing active management strategies such as express lanes, ramp metering, and running shoulder as well as the traditional intelligent transportation systems (ITS) functions such as incident detection and traffic monitoring. These applications rely on a network of roadway sensors to ensure that the control strategy matches the current traffic conditions. This work focused on data accuracy and maintenance of Microwave Vehicle Detection Systems (MVDSs), impact on the TMC applications, testing, and maintenance strategies. This work focused on data accuracy and maintenance of MVDSs systems, impact on the TMC applications, testing, and maintenance strategies. First, a literature review of the accuracy requirements for VDS in different agencies in the U.S was conducted. Interviews with staff in several Florida Department of Transportation (FDOT) districts were conducted to determine failure modes, data, and maintenance issues faced with respect to MVDSs. Field data were collected and analyzed to produce an assessment of the variation of MVDSs accuracy over time. Recommendations for acceptance testing, inspection, and accuracy monitoring are provided in the report.

State of the Practice

The state of practice consisted of a literature review and interviews with ITS engineers, maintenance personnel, and maintenance records review. The literature review was intended to find previous studies and minimum and maximum levels of accuracy in use in other states. A summary of the literature review on accuracy specifications is presented in Table A.

Table A: Minimum and Maximum Requirements for Accuracy of Vehicle Detection Systems

Traffic Variable	Minimum Accuracy	Maximum Accuracy
Speed	80	95
Volume	90	95
Occupancy	80	95

Speed and occupancy present the minimum accuracy bounds. Speed and accuracy are based on average values over the data collection interval and, as such are not sensitive to hardware data issues such as missing data or duplicated values. On the other hand, volume is a counting process, and it needs all the data in the interval to be accurate. Data duplication or omission are noticeable in the volume estimate.

A state of the practice session highlighted the current failure mode and issues faced by agencies in Florida with respect to MVDSs. The results for the state were summarized in a cause and effect diagram as follows:

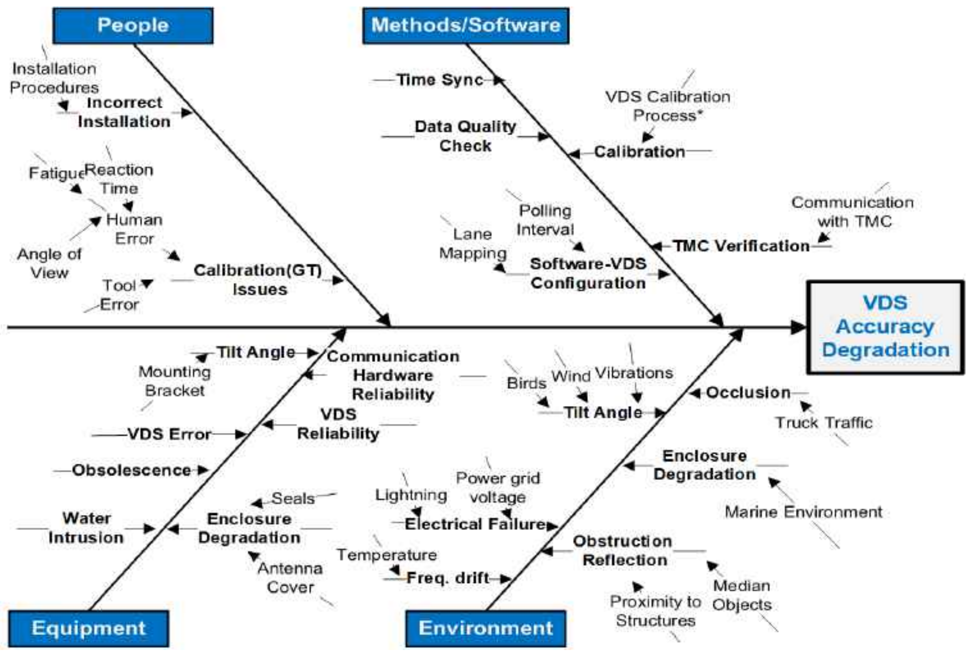

Figure A: Cause and Effect Diagram for Factors Affecting MVDS Accuracy

Field Data Analysis

Field data were collected from several agencies. MVDS data from different manufacturers were analyzed with respect to the acceptance criteria for accuracy stated in Standard 660. For the analysis it was necessary to establish a unit of inspection as the data collection interval. Accuracy was evaluated by finding the fraction non-conforming of data collection intervals. The data were analyzed to check for possible drifting over time. Figure A below presents an example of speed for three co-located MVDS's (ISS-G4, Wavetronix-HD, and Wavetronix SS-105) with respect to a loop detector using as ground truth. It is observed that lane 1 (closest to the MVDS) has some calibration issues but these are constant over time in three years (average slope was statistically 0). The data were constantly bias, which can be solved via recalibration. For lanes 2-4, over 90 percent of the intervals are within the specified limits. It is important to note that the accuracy rating is a scaled amount from zero to one, a 90 percent accuracy means that this is the average rating for the MVDS. In practice, it is also relevant to ensure that the majority of the intervals measured with the device will be conforming to the standard.

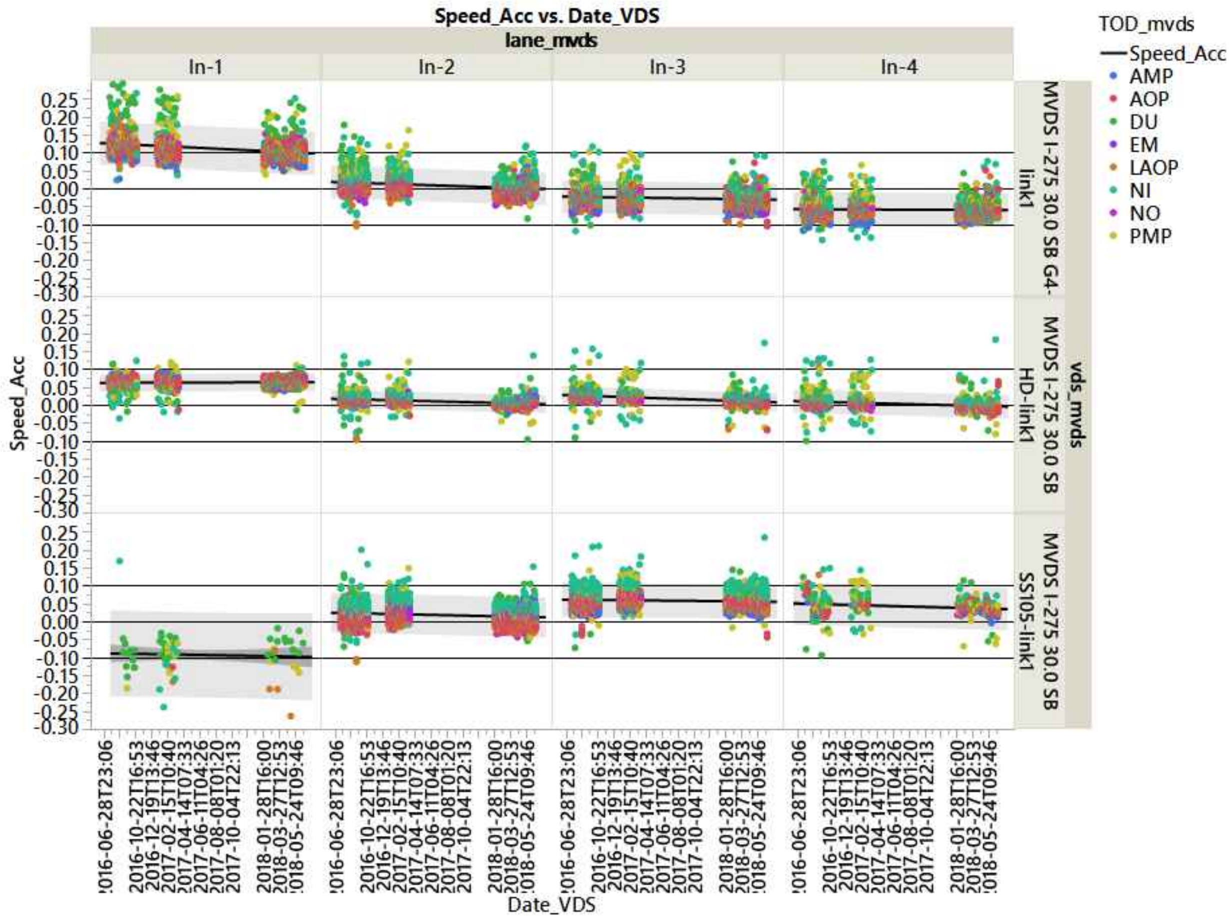

Figure B: Speed Accuracy over Time by MVDS Type by Lane Color Coded by Time of Day

Conclusions

- Data quality in detection systems is mostly due to installation, configuration, or software errors. For instance, in District 4, there are no reported incidents on the quality of the MVDSs in use.
- There was no evidence that data quality degradation occurred over time with respect to a reference loop detector, once a MVDS was calibrated. This was verified in three sites with data analyzed over several years.
- When comparing MVDS data with data from external systems, it is important to pay attention to synchronization issues to avoid overstating accuracy errors.
- Current detection equipment is capable of meeting the standards for speed and volume traffic conditions B, C, and D.
- Speed consistency (variability) is affected for all MVDS technologies for congested scenarios (LOS E, F). However, it still remains within the target average accuracy.

Recommendations

- Implement an automated MVDS time synchronization command periodically. The proposed frequency is once per day. This can occur at low traffic periods such as early in the day.
- Synchronization can be triggered from the TMC as a scheduled process via SunGuide, or it can be implemented as an automated feature on the MVDSs. If implemented in the MVDSs, the agency shall provide a time server in its network. The MVDSs shall provide the functionality to update its time at the designated schedule.
- Revise travel time segments periodically to ensure that calculation parameters are properly encoded.
- Revise lane mappings systematically for new MVDSs installations. Check for lane mapping errors and correct them.
- Designate a position at the TMC to detection issues. This person needs to be trained in MVDSs calibration and troubleshooting.
- Conduct MVDSs workshops with SunGuide database administrators, TMC operators, and MVDSs maintainer in common topics in MVDSs accuracy such as data collection, calibration, verification recommendations, basic troubleshooting, data management, etc. This will help to improve the current practices.
- Integrate SunGuide with maintenance and operations management (MOM) systems. Establish a MVDSs installation workflow that starts with SunGuide, and it is pushed to the MOM system. In this way, there is a single source of truth for MVDS information, and all the maintenance data can be exchanged between the two systems.
- For managed lanes application, conduct the calibration tests after all the roadway objects have been installed (e.g., delineators). This will ensure that the calibration procedure will be robust against median objects.
- Establish a set of priority detectors critical to system performance monitoring. This set of critical MVDSs will receive priority for maintenance and constant health and accuracy monitoring.
- Establish performance metrics that takes into consideration communication and detection failures separately.
- Establish a TMC procedure for verification and inspection of a MVDS installation. The procedure shall include calculations and acceptance criteria based on capabilities within reach of TMC operators using CCTV monitoring cameras. A spreadsheet tool was developed for this purpose.
- Save MVDSs configuration in in the central system, and refresh the configuration on the field MVDS after a certain period (e.g., quarterly). This process can be automated in SunGuide. In addition, testing for this feature as part of the TERL acceptance test is recommended.

- Test for power off/on recovery of MVDSs. Based on review of maintenance records after power outages, some detectors cannot come back to the same settings. The recommended testing is to turn power off/on and check for changes in accuracy or settings.
- Test for water intrusion as part of the Traffic Engineering Research Laboratory (TERL) approval tests. These tests shall simulate some extreme field conditions such as heavy rain in a hot day. To replicate field conditions, blow hot air over the microwave detector until the target temperature is obtained, and sprayed with water to test the seals and accuracy. This process can be repeated a number of times to verify performance.
- Revise surge protection procedures to ensure that the latest recommended practices are being followed in the field.
- Revise the reliability requirements for communication terminals. This element has the potential to disable the detection data transfer to the TMC and creates a weak link if its reliability is lower than that of the MVDSs.
- Revise installation procedure for mounting MVDSs and provide training material to installers. Installation requirements/training has to be flowed down to the field installer to ensure proper implementation.
- Design an MVDS package for new ITS deployments that includes requirements for remote reset capabilities for field equipment (e.g., reset detector, switch, UPS, clear ARP tables, etc.). In this way, basic troubleshooting can be shifted to the TMC to avoid mobilizing crews to resent different components.
- Create a reset MVDS routine in SunGuide to automatically attempt to bring an MVDS back to operation. This may include but is not limited to, turning off/on devices, clearing memory, and deploying last known configuration. If communication, power, and mechanical conditions remain the same and the device cannot be brought back to calibration status, then there may be some aspects to resolve with the MVDS manufacturer.
- Keep the current standards for speed, volume, and occupancy but apply the standards by traffic conditions, being stricter for AM/PM peak conditions. These will be the decisive criteria to recommend MVDS to be used in active traffic management applications (express lanes, running shoulder, ramp metering).
- Implement a true zero test for low volume conditions. This test shall be stricter for MVDS to be used in presence detection applications (queue detectors, wrong way detection). A confusion matrix is recommended for this traffic condition (e.g., number of false detections, number of omissions).

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1 Introduction

The road transportation system in the United States comprises more than 4.1 million miles of road which accommodate yearly more than 4 trillion passenger-miles and over 1.2 trillion ton-miles of for-hire and private truck freight (*1–3*). Decreases in the performance of the transportation system can potentially represent yearly losses of billions of dollars due to freight bottlenecks and delayed deliveries. In fact, in 2006, the United States Department of Transportation (USDOT) reported an estimated loss of $200 million. Added to that, travelers lost almost 4 billion hours and more than two billion gallons of fuel due to traffic jams (*4*). The Federal Highway Administration (FHWA) released a forecast in May 2016, estimating an increase in total vehicle miles traveled of approximately 18% until 2034 (*5*). With an ever-increasing vehicle population, transportation agencies face many challenges to maintain acceptable levels of mobility while maximizing roadway safety. Traffic management centers (TMCs) are implementing active management strategies such as express lanes, ramp metering, and running shoulder as well as the traditional Intelligent Transportation Systems (ITS) functions such as incident detection and traffic monitoring. These applications rely on a network of roadway sensors to ensure that the control strategy matches the current traffic conditions. This work focused on data accuracy and maintenance of microwave vehicle detection systems (MVDSs), impact on the TMC applications, testing, and maintenance strategies. First, a literature review of the accuracy requirements for VDS in different agencies in the U.S was conducted. Interviews with staff in several Florida Department of Transportation (FDOT) districts were conducted to determine failure modes, data, and maintenance issues faced with respect to MVDSs. Field data were collected and analyzed to produce an assessment of the variation of MVDSs accuracy over time. Recommendations for acceptance testing, inspection, and accuracy monitoring are provided in the report.

Vehicle Detection Systems (VDSs) and traffic surveillance technologies are an important part of ITS, gathering most of the data that will be shared, analyzed, transported, and applied for improvements in safety and mobility across all modes of travel. VDSs and traffic surveillance technologies commonly monitor speed, vehicle counts, headway, and gap measurements, vehicle classification, presence detection, and weigh-in-motion data. In the last 20 years, several studies were conducted by departments of transportation and research institutes to examine traffic data collection capabilities of diverse sensor types and technologies. The most promising non-intrusive technologies were studied and tested at the component level, motivated by the need to assess eventual drawbacks in comparison with common techniques such as inductive loops. Accuracy and consistency of detector data have been continuously studied.

1.1 Overview of Vehicle Detection Technologies

VDS are available in a vast range of types and technologies, requiring different installation characteristics and providing different functionalities and data types. The sensors can be described, in a high level view, as having three main functionalities. The first one is detecting the passage or presence of a vehicle in an area of interest, called a detection zone. The second functionality processes this signal, converting it into an electrical signal. The third functionality is a data processing device that converts electrical signals into traffic parameters. One of the most basic usages for a VDS is for presence detection, applicable for example to traffic signals. More advanced applications can be found in highways, where VDSs provide key traffic parameters such as traffic volume, speed, road occupancy, and vehicle classification. Figure 1 highlights the raw traffic data usually obtained from VDSs.

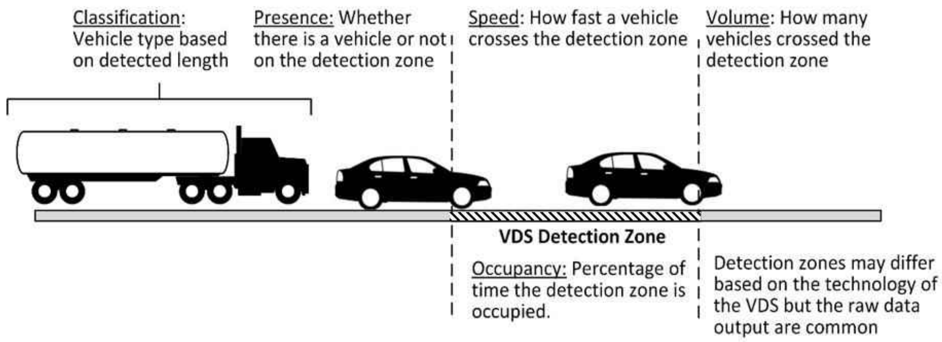


Figure 1: VDS Data Types

The Traffic Detector Handbook published by the FHWA in 2006 classifies the sensors within two categories, using the terminology in-roadway and over-roadway (*6*). The in-roadway sensor category comprises those sensors that are embedded in the pavement or in the subgrade of the roadway, taped or otherwise attached to the surface of the roadway. On the other hand, the over-roadway sensors are mounted above the roadway itself (overhead mounting position) or alongside the roadway, offset from the nearest traffic lane (side-fire mounting position).

The most common examples of in-roadway sensor are inductive loop detectors, requiring cuts in the pavement. Weigh-in-motion sensors are another example of sensors that are embedded in the pavement. Magnetometers might be intrusive if embedded on the pavement, or placed underneath from the side of the road or under a bridge. In-roadway sensor types also include sensors that are mounted on top of the roadway surface: microloops, pneumatic road tubes, and piezoelectric tubes. The in-roadway sensors are considered mature technologies, well understood and extensively applied. One of the main downsides of their use is the need to disrupt traffic for installation and repair. The process also reduces the pavement lifespan, potentially generating infiltrations due to pavement deformation or sealant failure (*6*).

Over-roadway sensors include machine vision based sensors, relying on cameras mounted on poles adjacent to the roadway, traffic signals, or poles with arms over the roadway to enable video analysis; microwave detectors, sidefire or overhead mounted; ultrasonic, infrared, and laser sensors, commonly mounted over the lanes to be monitored (*6*).

Outside of the two categories there is a third type of detection systems, usually referred to as Probe Data Detection Systems (PDDS). This type of detection system is non-intrusive and relies on the use of Automated Vehicle Identification (AVI) technologies to provide a unique signature for a vehicle along with a time stamp at predefined locations. The most common identification features used by AVI systems are license plates using optical character recognition, toll transponders using radio frequency identification and Bluetooth® readers. The time-stamped identifiers are used to measure travel time and average speed between two or more detection locations.

1.2 Uses of VDS Data

Transportation system requires monitoring and communication infrastructure of which VDS components are a key part. Intelligent Transportation Systems (ITS) typically comprise these functionalities. In Florida, the interstate system is monitored and managed using ITS Infrastructure. These monitoring systems generate traffic data consumed by other systems for different applications. These applications may have diverse requirements with respect to accuracy, aggregation level, and life cycle of the input data. For example, for long-range planning, data are aggregated over time and roadway segments. Examples of highly aggregated data include Average Annual Daily Traffic (AADT) and Vehicle Miles Traveled (VMT). On the other hand, real-time traffic monitoring such as detecting a queue backing up on an interstate site-specific data with little or no aggregation over a shorter life cycle (polling cycle of 20-30 seconds). Other consuming applications will have data with medium aggregation level over time or roadway segments such as performance metrics and reporting. Fluctuations on VDS accuracy propagate to these consuming applications affecting their performance. Figure 2 presents the hypothesized relationship between data life cycle, aggregation level and consuming applications.

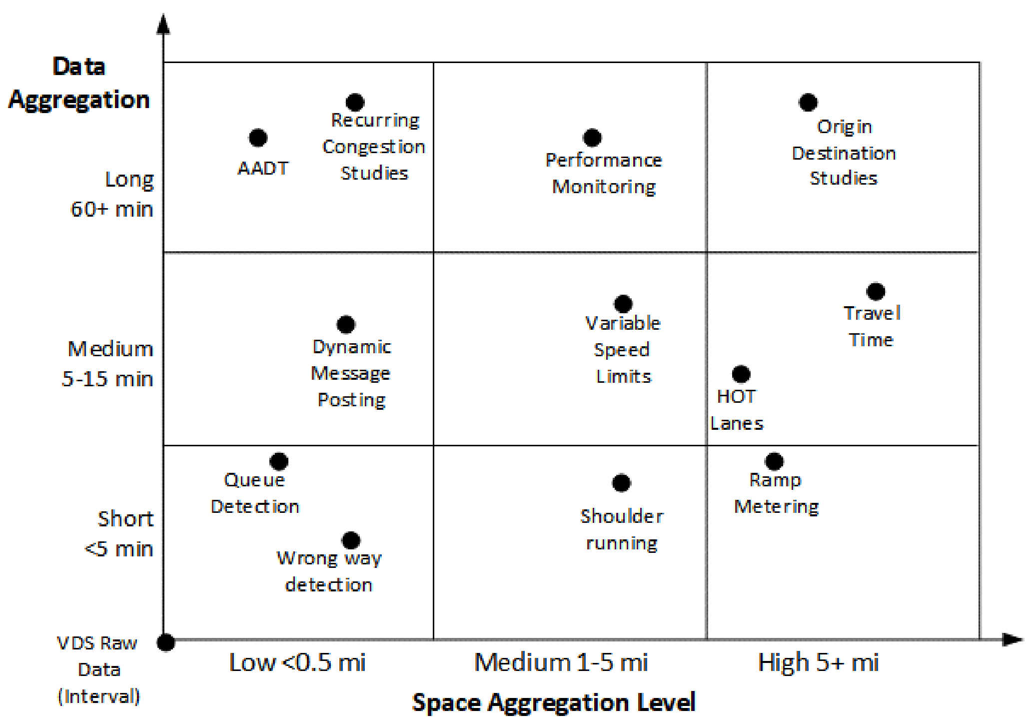


Figure 2: VDS Data Related to TMC Applications

For real time operations, low aggregation is used. This means that individual detector data accumulated in short time span are analyzed to make a decision. Once the decision is made and executed the processed data become obsolete. The life cycle for these types of data is very short. Some of these data may be kept for auditing purposes. For reporting performance metrics for the hour or over a day, data can be aggregated or rolled up on the appropriate intervals (e.g., hourly volumes counts per lane). For long range transportation planning analyses involving traffic forecasting, volumes can be aggregated by roadway and direction. Aggregated data at roadway segment are used to calibrate travel demand models for transportation planning. The effect of VDS accuracy on the performance of the traffic data consuming systems needs to be addressed to prioritize maintenance resources, minimizing costs and reaching operational goals for the transportation system

1.3 Accuracy and Consistency

All traffic sensors are subject to some sort of error. Depending on factors such as detection technology, mounting scheme, or even environmental factors, specific types of errors are more prone to happen than others. For example, inductive loop detectors could double count vehicles in the process of changing lanes over the detection zone, microwave radar detectors are subject to occlusion due to high profile vehicles, and video detection performance degrades with poor lighting or rainy conditions.

In that sense, accuracy can be defined as the level of agreement between a data set and another source assumed to be correct (ground truth data) (*7*). According to Montgomery accuracy is the ability of an instrument to measure the true value correctly on average, while consistency is a measure of the inherent variability of the measurement system (*8*). These concepts are visually represented on Figure 3.

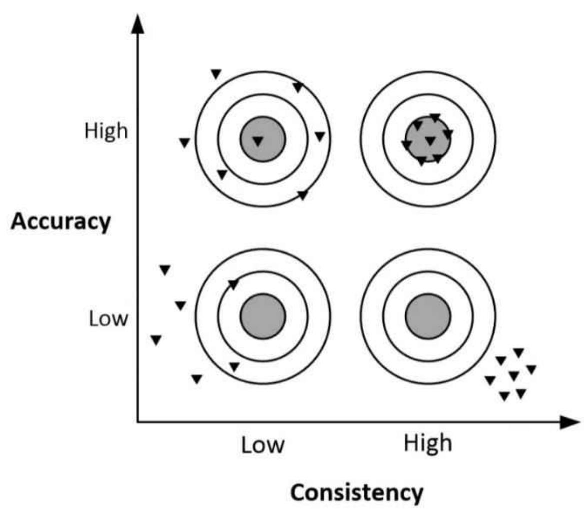


Figure 3: Accuracy and Consistency General Concept

In an ideal system, all measurements will be closely located around the target, indicated on Figure 3 by high accuracy and high consistency. A highly consistent system but with low accuracy will have measurement highly packed in an area but off target. In cases where the consistency is low it is possible to have a highly accurate system on average, but the measurements will be scattered around the target, most of the time off-target. The worst-case scenario is represented by a low accuracy low consistency pair, where measurements are highly disperse and off-target on average.

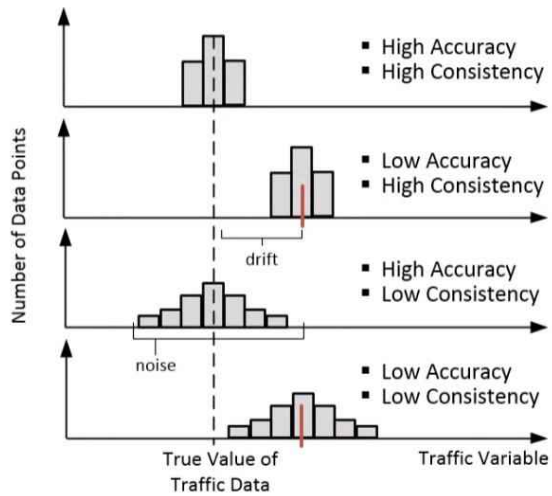


Figure 4: Accuracy and Consistency Concepts for Traffic Data

An example of an application of these concepts to VDS data are presented in Figure 4. The top chart (High Accuracy High Consistency pair) represents cases where the VDS is working properly, in a way that the obtained measurements are expected to be closely distributed both sides of the true value. The second chart from top to bottom (Low Accuracy High Consistency pair) represents cases where the VDS systematically drift its measures from the true value. The bottom two charts represent cases where the VDS shows consistency problems. In those cases, if there is no accuracy problems (High Accuracy Low Consistency pair) the measurements will be, on average on the true value, but with excessive noise.

1.4 Requirements Testing Specification for VDS

FDOT Specification 660 (*9*) contains a set of comprehensive VDS requirements of various types including functional, performance, physical construction, electrical, mechanical, and installation requirements. Specification 660 is organized on six sub items: Description, Materials, Installation Requirements, Warranty, Method of Measurement, and Basis of Payment (from 660-1 to 660-6).

Section 660-1 briefly describes the purpose of the section, related to furnishing and installing vehicle detection systems in accordance with contract documents. Within the description is also stated that the used material must meet the requirements of the current specification and also be listed on the Department’s Approved Product List (APL).

The next section (660-2 Materials) begins with a classification of VDS and data collection systems, first according to their functional types and then by technology type. The functional classification lists three possible types: Vehicle Presence Detection Systems, Traffic Data Detection Systems and Probe Data Detection Systems. Vehicle presence detection systems are mostly used in signalized intersections and in freeway access ramps, producing a corresponding output any time that a vehicle occupies the detection zone. Traffic Data Detection Systems are usually distributed along the road providing presence, volume, occupancy, and speed data for the lanes they are configured to monitor. Probe Data Detection Systems provide speed data and travel times for a road segment, using automatic vehicle identification (AVI) technologies to establish a unique identifier for each vehicle. In the sequence technology types are described and relevant requirements for each technology type are presented. The technologies covered are: Inductive loop, video, microwave, wireless magnetometer, and AVI systems. The next topic covered in section 660-2 is the performance requirement for each one out of the three detection types (660-2.2, 660-2.3, and 660-2.4).

Item 660-2.2 addresses vehicle presence detection system performance requirements, establishing a minimum accuracy of 98%. In order to verify conformance with the accuracy requirements, item 660-2.2.1 defines how to obtain sample data from the VDS and compare to ground truth data obtained at the same period. The item states that sample data shall be collected over several time periods under a variety of traffic conditions, weighting the different conditions over the course of a 24-hour period.

2 Literature Review: Minimum Accuracy Standards across the U.S.

In an effort to contextualize the minimum VDS accuracy requirements from Florida in a countrywide perspective, the relevant publications from several departments of transportation were reviewed and summarized. Table 1 presents this summary of minimum accuracy standards published by several states. The pass/fail criteria are reproduced here exactly as originally stated in the source documents.

Table 1: Minimum Accuracy Standards Across the Country

State	Detection Technology	Variable	Stated Pass/Fail Criteria
Florida	Microwave, Video, Magnetic and Acoustic Vehicle Detection System(*9*)	Occupancy	90% Accuracy
		Speed	90% Accuracy
		Volume	95% Accuracy
California	Microwave Vehicle Detection System (*10*)	Classification	Accurate to 90% of the ground truth
		Occupancy	Accurate to 85% (5-minute samples, 15 minutes period). Accurate to 90% for any lane and 95% for all lanes combined.
		Speed	Accurate to 95% of the ground truth
		Volume	Accurate to 95% (5 minutes sample) and 90% (30 seconds sample) of the ground truth
Georgia (City of Forest Park)	Video Vehicle Detection System (*11*)	Occupancy	95% (no more than +/- 5% missed actuations)
		Presence	95% (no more than +/- 5% error in missed actuations)
		Speed	95% (no more than 5% error in speed calculation)
		Volume	95% (no more than 5% missed actuations)
	Microwave Vehicle Detection System (*11*)	Classification	Maximum error level of ± 10%
		Occupancy	Maximum error level of ± 10%
		Presence	Maximum error level of ± 5%
		Speed	Maximum error level of ± 10%
		Volume	Maximum error level of ± 8%

Table 1: Minimum Accuracy Standards Across the Country (continued)

State	Detection Technology	Variable	Stated Pass/Fail Criteria
	Magnetometer Vehicle Detection System (*11*)	Classification	Maximum error level of ± 10%
		Occupancy	Maximum error level of ± 10%
		Presence	Maximum error level of ± 5%
		Speed	Maximum error level of ± 10%
		Volume	Maximum error level of ± 8%
Mississippi	Video Vehicle Detection System (*12*)	Classification	Correct Classification of at least 80% of the vehicles
		Stopped Vehicle	Detection of 95% of all stopped vehicles
		Presence	98% accurate in all weather conditions
		Speed	Within ± 10% of the ground truth
		Volume	Within ± 5% of the ground truth
	Magnetometer Vehicle Detection System (*13*)	Classification	Within ± 10% of the ground truth.
		Occupancy	Within ± 5% of the ground truth.
		Presence	Within ± 1% of the ground truth.
		Speed	Within ± 10% of the ground truth.
		Volume	Within ± 8% of the ground truth.
Michigan	Microwave Vehicle Detection System (*14*)	Occupancy	Accuracy required: ± 10%
		Speed	Accuracy required: ± 10%
		Volume	Accuracy required: ± 5%
	Video Vehicle Detection System (*15*)	Presence	98% accurate in good weather conditions and 96% under adverse conditions.
New Mexico	All Technologies (*16*)	Occupancy	Accurate to 85% (5 minutes sample) and 95% (any period of time that vehicles are stationery or congested traffic) of the ground truth
		Speed	Accurate to 95% of the ground truth

Table 1: Minimum Accuracy Standards Across the Country (continued)

State	Detection Technology	Variable	Stated Pass/Fail Criteria
		Volume	Accurate to 95% (5 minutes sample) and 90% (30 seconds sample) of the ground truth
New York	Video Vehicle Detection System (*17*)	Occupancy	Within ± 20% of the ground truth.
		Presence	98% accurate in all weather conditions.
		Speed	Within ± 20% of the ground truth.
		Volume	95% true counts (normal weather) 90% true counts (adverse weather)
	Acoustic Vehicle Detection System (*18*)	Occupancy	Within ± 10% of the ground truth
		Speed	Within ± 10% of the ground truth for speeds above 20 mph
		Volume	Within ± 5% of the ground truth for up to the 4th lane and ± 6% for the 5th lane.
	Microwave Vehicle Detection System (*19*)	Presence	Accurate to 95% of the ground truth
Texas	Non-Intrusive Detectors (*20*)	Occupancy	85% overall accuracy
		Speed	85% overall accuracy
		Volume	90% overall accuracy
Utah	Non-Intrusive Detectors	Occupancy (*21*)	Within ± 5% of ground truth
		Speed (*22, 23*)	Within ± 5 mph of ground truth
		Volume (*24*)	Within ± 10% of ground truth

Countrywide the relevant literature revealed in some cases, accuracy standards fluctuating depending on weather condition or lane of traffic. The lower bounds on minimum accuracy standards for speed and occupancy were found to be as low as 85% of the ground truth (*20*). For volume this value was 90% as presented in (*10–24*). The minimum accuracy standards for the acceptance tests change from state to state, but are in general consistent among the majority of the states. In Florida, it is expected that the detectors are 90% accurate for occupancy, 90% accurate for speed and 95% accurate for volume.

2.1 VDS Performance Studies across the Country

This section presents a literature survey of relevant VDS performance assessment studies carried out across the U.S by different Departments of Transportation. The main findings and relevant discussion from each study were summarized in Figure 5.

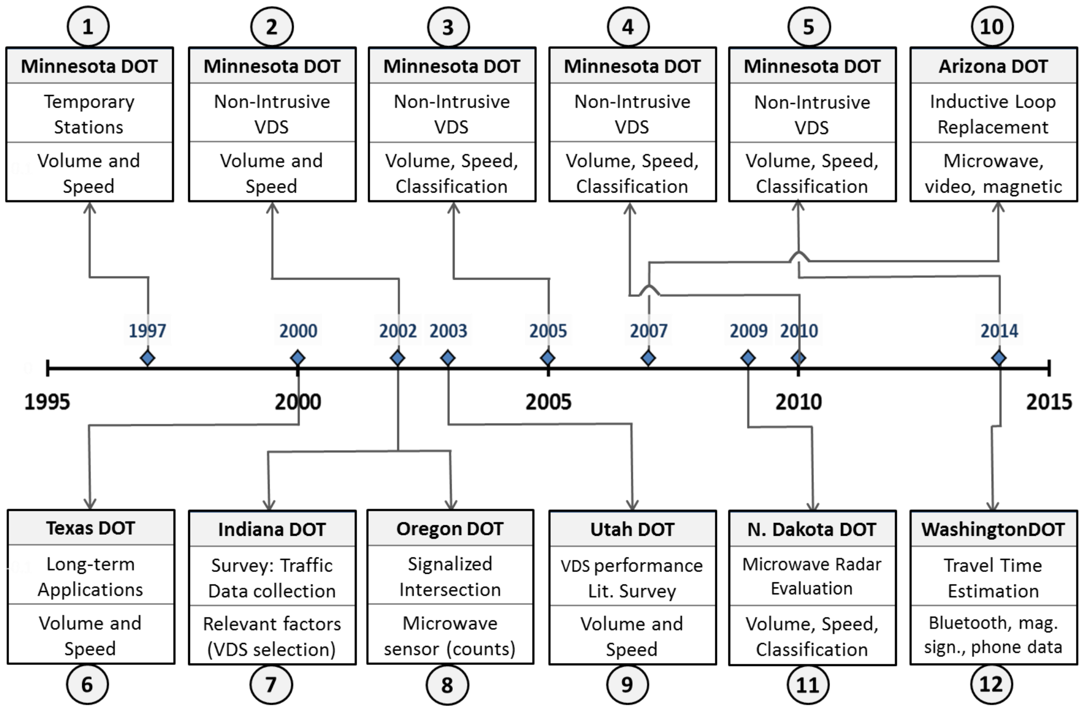


Figure 5: Performance Studies Overview

The main sorting factor used here is to chronologically present the studies, with one exception made for the sequence of studies performed by the Minnesota DOT (studies 1 through 5). The discussion in the following paragraphs starts by covering the Minnesota DOT studies in chronological order and in the sequence addresses all other DOT studies, also in chronological order.

The first study (Figure 5, number 1), entitled “Field Test of Monitoring Urban Vehicle Operations Using Non-Intrusive Technologies”, and from the Minnesota Department of Transportation jointly with the SRF Consulting Group seeks to provide useful information on non-intrusive technologies and specific device performance. The study was performed over the course of two years, evaluating 17 sensors within seven different technologies in several environmental and traffic conditions, at both freeway and intersection location. The evaluation focused on the feasibility of applying the technology in temporary count locations with a typical 48-hour traffic counts, but also considered permanent applications like traffic signals, ramp metering and Intelligent Transportation System applications. The study included volume, speed, and classification data analysis and also considered ease of setup, reliability, cost, and flexibility. The baseline for the data comparison was established using pre-installed inductive loops. Manual counts for volume were made from video tapes of traffic while for speed both radar gun and probe vehicles were used, using the obtained factors to adjust the baseline.

Video detection and passive acoustic sensor data from an overhead mounting in the freeway were found to be within four and ten percent of the ground truth volume data. Pulse ultrasonic, Doppler microwave radar, passive magnetic, passive infrared, and active infrared reported data were found to be within three percent of the ground truth volume data. For speeds, in general, all devices were within eight percent of the ground truth. Doppler microwave, video, and radar microwave were the most accurate detection technologies at measuring speeds. Weather condition was considered to have minimal affect in performance. Lighting condition was the major environmental factor affecting performance of video detectors, mainly during the transition from day to night.

It was found that passive infrared, microwave radar, Doppler microwave, and pulse ultrasonic are the technologies that met the requirements in most of the tests. The authors noted that the performance varies more from one device to another within the same technology than from one technology to another. From that, the authors suggest that it is important to select a reliable, well designed and robust detector, rather than limit the selection to a technology type (*25*).

In 2002, the Minnesota DOT expanded the previous studies, conducting a comprehensive study to evaluate non-intrusive traffic detection technologies (Figure 5, number 2). The study entitled "Evaluation of Non-Intrusive Technologies for Traffic Detection" was motivated by the need of understanding the benefits and limitations of the most promising non-intrusive technologies. The parameters evaluated were volume, speed, and presence, in nine different sensors technologies. Inductive loops provided the baseline data used as ground truth for volume and speed while, manual observations were used for presence. To verify the baseline data quality for volume, manual counts from video images were made.

The reported accuracy was obtained by measuring the absolute percent difference between each sensor and the baseline during the 24-hour test period, divided into 15-minute intervals. The sensors were mounted at the freeway test site at the vendor's recommended height and offset. The report seeks to provide insight into the technologies by providing an overview of sensor performance in key areas. Table 2 summarizes the accuracy results (*26*).

Table 2: Summary of Accuracy Results

Source: (*26*)

Sensor	Vendor	Technology	Mount Location	Volume Accuracy	Speed Accuracy
ASIM IR 254	ASIM Technologies Ltd	Passive Infrared	Overhead	10.0%	10.8%
ASIM DT 272		Passive Infrared, Ultrasonic	Overhead	8.7%	N/A
			Sidefire	0.8%	N/A
ASIM TT 262	ASIM Technologies Ltd	Passive Infrared, Ultrasonic, Radar	Overhead	2.8%	4.4%
Autoscope Solo	Image Sensing Systems	Video	Sidefire	2.0% to 2.7%	5.7% to 7.4%
			Overhead	1.5% to 2.2%	2.5% to 7.0%
Autosense II	Schwartz Electro-Optics Inc.	Active Infrared	Overhead	0.7%	5.8%
SmarTek	SmarTek Systems Inc.	Passive Acoustic	Sidefire	6.7% to 12.0%	4.8% to 6.3%
VIP D	Traficon NV	Video	Sidefire	1.9% to 3.7%	2.3% to 7.7%
			Overhead	2.7% to 4.8%	3.3% to 7.2%
Canoga	3M	Magnetic	Under Pavement	2.3% to 2.5%	1.4% to 4.9%
			Under Bridge	1.2%	1.8%

In 2005 the Minnesota DOT studied in depth three distinct sensors: Wavetronix SmartSensor SS105, the EIS RTMS, and SmarTek SAS-1 (Figure 5, number 3). The study entitled “Evaluation of Portable Non-Intrusive Traffic Detection System” covered mounting techniques and analyzed detector accuracy.

For the lanes where loop sensors were available, samples were taken during 24-hour test periods, using the loop detectors as baseline. For the other lanes it was adopted two-hour manual counts using video-tapes as baseline. The researchers also analyzed weather records to verify eventual degradations in performance. The result summary for the tests is summarized in Table 3:

Table 3: Overall Results Summary for Volume and Speed Detection Error

Source: (*27*)

		SS105	RTMS	SAS-1
Volume Detection		1.4% to 4.9%	2.4% to 8.6%	9.9% to 11.8%
Speed Detection		3.0% to 9.7%	4.4% to 9.0%	5.6% to 6.8%
Impacts from	Heavy Traffic	No	No	Yes, undercount
	Weather	No	No	No
	Barrier	Minimal	Moderate	Not tested

The sensors from Wavetronix and EIS were also tested for accuracy in length-based classification. For the porpoise of the study three classes were considered: Small Vehicles ranging from 0 to 25 ft., Medium Vehicles ranging from 25 to 45 ft., and Large Vehicles ranging from 45 to 120 ft. The baseline was collected by manual observation. The results are summarized in Table 4.

Table 4: Results Summary for Length-Based Classification Error

Source: (*27*)

	SS105	RTMS
Lane 1 (closest)	0.9% to 5.6%	1.2% to 4.4%
Lane 2	0.6% to 4.7%	0.2% to 1.2%
Lane 3	0.4% to 1.5%	0.4% to 1.4%

Among other findings, the research concluded that the tested sensors were able to collect accurate traffic data under both free-flow and heavy traffic, as long as the sensor is properly calibrated (*27*).

The fourth study from the Minnesota DOT, published in 2010 and entitled "Evaluation of Non-Intrusive Technologies for Traffic Detection" (Figure 5, number 4) builds on the previous ones, evaluating non-intrusive detectors. The field tests were emphasized in heavy traffic condition and special attention was dedicated to changes in weather and lighting conditions. Table 5 summarizes the study findings.

To define the baselines for data comparison, the study uses three approaches. The baseline data came from inductive loops already available in the test site. To analyze the loop performance in establishing a baseline video recording and manual verification was employed. For speed, the baseline error was within one to two mph and for axle spacing between 0.1 to 0.2 feet. For volume the baseline was generally accurate, with exception when lane changes occurred (double counts) and for stop-and-go conditions. For these cases manual count was performed to provide a better quality baseline.

Table 5: Test Results Summary

Adapted from: (*28*)

		Wavetronix Smart Sensor HD	GTT Canoga Microloop	PEEK AxleLight	TIRTL	Miovision
Technology		Radar	Magnetomer	Laser	Infrared	Video
Mount Position		Sidefire	Under Road	Sidefire	Sidefire	Sidefire
Volume Error	LOS A-D	< 2%	2.5%	5.4%	3.8%	< 2.0%
	LOS E-F	2 to 20%	2.5%	N/A	N/A	< 2.0%
Speed Error (LOS A-E)		< 1 mph	< 1 mph	2 mph	1.2 mph	N/A
Classification (LOS A-D)		1.6’ to 2.0’	3.7’ to 4.0’	1.0’ to 2.0’	< 1.0’	Not tested
Ease of Installation	Portable	+	-	-	-	+
	Permanent	+	-	-	-	N/A
Ease of Calibration		+	+	-	+	+
Performance	Heavy rain	+	+	Not tested	Not tested	Not tested
	Snow/ fog	+	+	Not tested	Not tested	Not tested

The SmartSensor HD performed similarly to loops for speed and volume accuracy, with error ranges within 1.6% for volume and less than one mph for speeds. The absolute error for classification was 1.6 feet for small vehicles and 2.8 feet for large trucks. A detailed vehicle-by-vehicle analysis showed significant undercounting performance during periods of heavy congestion. For the Wavetronix SmartSensor HD the error in volume also depends on the lane, due to occlusion.

The GTT Canoga Microloops also performed as accurately as the loops, with error ranges within 2.5% for volume and less than one mph for speed. The absolute error for classification was 3.7 feet for small vehicles and 4.0 feet for large trucks. Similarly to loops, the GTT Canoga Microloops double counted due to lane changes.

The PEEK AxleLight volume and classification accuracy was dependent on the classification scheme selected, due to the lack of a sensor to determine gaps between vehicles. Closely spaced vehicles were easily grouped. The calibration process required experience through trial and error and the locations for setup are limited, requiring specific conditions to attach the sensor. The TIRTL demonstrated speed and axle classification accuracy typically within 2%. The same consideration about classification schemes made for the PEEK AxleLight applies to the TIRTL sensor that requires significant traffic control for portable deployment. One set of sensors was capable to cover four lanes of bidirectional traffic.

The Miovision sensor volume accuracy was typically within 2.2% of manual counts. The system may be installed either on a pole or self-standing on a tripod and has quick setup. The system is intended to provide volume, no speed data are reported and the classification procedure is rudimentary.

The study highlights the introduced classification capabilities, more robust in comparison with the technologies from the previous two phases of the study. The classification data analysis required time-consuming data analysis but revealed that, if properly configured, the sensors perform accordingly with vendor claims. Converting the data to standard classification schemes such as the FHWA scheme usually introduces errors. The study concluded that there were overall improvements in sensor performance when compared to the previous phases.

In 2014 the Minnesota DOT conducted the "Traffic Data Collection Improvements" study (Figure 5, number 5), evaluating traffic detection sensors, to investigate non-intrusive low cost alternatives to traditional methods such as tubes and inductive loops.

The approach adopted was to collect data over the course of one week in phase one and two weeks in phase two, comparing it to the data provided by a previously installed test site, equipped with dual loop-piezo-piezo-loop detectors, capable of providing accurate volume, length-based classification, and speed data. Out of the three weeks of collected data, the researchers selected three 24-hour periods to conduct extensive studies. To estimate the volume percent error, the entire 24-hour period data from each detector was summed and divided by the total number of vehicles manually counted. For speed error estimations sensor data and baseline data were compared per 15-minute bins. For classification 4 categories were considered, basing in the vehicle length: Motorcycle, small vehicles, medium vehicles and large vehicles. Table 6 summarizes the accuracy findings.

Table 6: Data Accuracy Findings

Source: (*29*)

Sensor	Volume Percent Error	Speed Percent Error	Length Classification Percent Error
COUNT cam	2.4%	N/A	7.1%
Scout	1.8%	N/A	8.4%
Radar Recorder	1.0%	1.2%	7.7%
Wavetronix HD	2.4%	1.2%	4.5%
Houston Radar	4.1%	3.5%	N/A
Sensys	1.5%	5.9%	14.8%
Road Tubes	6.8%	4.2%	16.5%

The study presents a summary of the overall findings in a qualitative assessment of each sensor ranking it in between the three categories: Excellent, Good or Poor. Considerations were made for different aspects: Installation, communication, data accuracy, integration, and post processing. Regarding accuracy, most detectors were classified as excellent. Exceptions for volume detection accuracy were made for the Doppler Microwave Houston Radar and Road Tubes. Both detectors were classified as 'Good', having volume error within 3% and 10%. For

Speed detection the Sensys Magnetometer was also classified as ‘Good’, presenting speed detection error within five and ten mph. For classification accuracy, the Sensys Magnetometer and the Road Tubes were classified as ‘Good’, presenting data ranging from 10% to 20% from ground truth (*29*).

The sixth study reviewed (Figure 5, number 6), entitled “Initial Evaluation of Selected Detectors” by the Texas DOT from 2000, studied the performance of three detectors: 3M non-invasive Microloops, Peek VideoTrak 900 VIDS and the SmarTek Acoustic Sensor SAS-1. The baseline data for all count accuracy comparisons came from either manual observation or from inductive loops, while for speed comparison the baseline came from a RTMS detector from Electronic Integrated Systems (EIS), carefully calibrated using a Pro Laser II Infrared Lidar System. The basis of comparison adopted for speeds was 1-minute intervals. To evaluate the detectors, the researchers used the following criteria: ease of setup, ease of calibration, cost, and count and speed accuracy.

For count accuracy, the 3M Microloops was tested in normal flow and also during stop-and-go conditions. For stop-and-go conditions 93% of the 5-minute intervals (13 of the 14) were within 5% error. The remaining interval was between 5% and 10% error. Overall the Microloops were 99.4% of the time within 5% error when dual probes were used and 94.5% of the time within 5% error for single probes. For the Peek Video Trak 900 and the SAS-1 the authors highlighted that significant degradation in performance occurred during wet weather. Also, the Peek Video Trak 900 had significantly worse after dark accuracy, compared to daytime.

Regarding speed accuracy, the tests indicated that the 3M Microloops was the most accurate, being capable of predicting one-minute intervals average speed within ± 7.3 mph of the ground truth 95% of the time. The researchers also noted that the 3M Microloops detector wasn’t affected by the rain, as expected. Speed accuracy results for the Peek Video Trak 900 indicated a mean of +1.4 mph with a standard deviation of 6.9 mph, while the SAS-1 indicated a mean of -0.5 mph and a standard deviation of 4.84 mph. Table 7 summarizes the effect of the wet weather in each sensor considered (*30*).

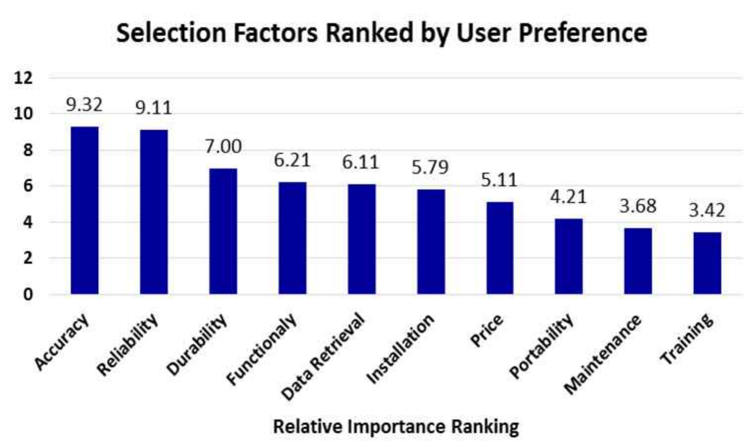
Table 7: Count Error Comparison for Dry and Wet Weather

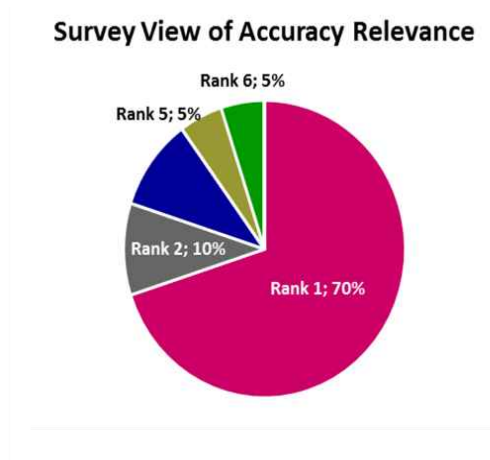
Adapted from: (*30*)

	Peek Video Trak 900			SAS – 1		
Error Range (%)	Dry Weather (% of time)	Wet Weather (% of time)	(Dry to Wet)	Dry Weather (% of time)	Wet Weather (% of time)	(Dry to Wet)
0 to 10	92.9%	39.2%	↓ 53.7%	96.5%	20.0%	↓ 76.5%
10 to 20	6.5%	36.7%	↑ 30.2%	3.5%	37.5%	↑ 34.0%
20 to 30	0.6%	21.6%	↑ 21.0%	0.0%	42.5%	↑ 42.5%
30 to 40	0.0%	0.0%	-	0.0%	0.0%	-
40 to 50	0.0%	2.5%	↑ 2.5%	0.0%	0.0%	-

In 2002, the Indiana DOT sponsored the study "Counting Device Selection and Reliability Synthesis Study" (Figure 5, number 7) to perform an extensive survey of both intrusive and non-intrusive traffic detection technologies, proposing a systematic method to be used in the detection device selection process.

As part of the study, the authors conducted a survey with personnel responsible for traffic data collection in different Departments of Transportation and districts within the departments. From the 47 surveys sent, the authors obtained 24 responses from the following states: California (5 responses), Texas (5 responses), Florida (4 responses), Minnesota (4 responses), Indiana (3 responses), and New York (3 responses). The survey was conceived to gather information about the respondent (including for example years of experience in the field), relevance perception of different factors when purchasing new devices, and also asks respondents to evaluate the products currently being used in their district. The respondents had an average experience on the field of over eight years. According to the survey the rank of importance prioritizes accuracy, followed by reliability, as show in Figure 6(a). The survey also revealed that 90% of the respondents rank accuracy as one of the three most important factors, being the most important 70% of the time, as shown in Figure 6(b) (*31*).





(a) (b)

Figure 6: Selection Factor Preference and View of Accuracy Relevance
Adapted from: (*31*)

In 2002 the Oregon DOT evaluated the Remote Traffic Microwave Sensor (RTMS) manufactured by Electronic Integrated Systems (EIS) to determine its viability as a detector device in a signalized intersection (Figure 5, number 8). The study analyzed the vehicle count data provided by RTMS comparing it against the data provided by inductive loops. To validate the ground truth source, the researchers conducted manual counts during one hour of commute traffic, characterized by high density and lane changing behavior. The study considered 15-minute intervals of vehicles counts for both detectors, from 6:00 am to 8:00 pm during four weeks.

The researchers noted that the RTMS systematically undercounted (see Table 8). Confidence intervals were analyzed and a two-sample t-test was performed, showing that the difference between the mean counts (5.7%) is statistically significant. Nevertheless the study concluded that the RTMS would perform as expected for traffic monitoring and as a signal controller. (*32*)

Table 8: Two Sample T-Test and Confidence Intervals

Source: (*32*)

Variable	n	Mean	St. Dev.	Standard Error	95% C.I.
Inductive Loops	1,336	124.055	33.951	0.929	122.232, 125.877
RTMS	1,336	117.314	31.832	0.871	115.605, 119.022

In a research from 2003 sponsored by the Utah DOT (Figure 5, number 9), a series of previous studies were compiled, organizing the information by technology, sensor type, mounting location and accuracy performance. Part of the results of the study is reproduced here in Table 9 (*33*).

Table 9: Error Rates of Detector Devices in Freeway Field Tests

Adapted from: (*33*)

Technology	Sensor	Mounting Location	Accuracy Performance		Study Year
			Counts	Speed	
Inductive Loops	Saw-Cut	Pavement	3%	1.2% to 3.3%	2002
	Saw-Cut	Pavement	2%	5% to 10%	2000
	Preformed	Pavement	2%	2% to 5%	2000
Magnetic	3M microloop	Pavement	2.5%	1.4% to 4.8%	2002
	3M microloop	Bridge	1.2%	1.8%	2002
	3M microloop	Pavement	5%	μ: -0.25 mph 3.6 mph	2000
	SPVD	Pavement	1% (Phoenix) 10% to 12% (Florida)	N/A	1996
Active Infrared	Autosense I	Overhead	2.4%	N/A	1997
	Autosense II	Overhead	0.7%	5.8%	2002
	ASIM IR 224	Overhead	1%	N/A	1997
	ASIM IR 254	Overhead	10%	10.8%	2002
	Siemens PIR-1	Overhead	10%	N/A	2000

Table 9: Error Rates of Detector Devices in Freeway Field Tests (continued)

Technology	Sensor	Mounting Location	Accuracy Performance		Study Year
			Counts	Speed	
Microwave	Accuwave 150LX	Overhead	10%	N/A	2000
	TDN 30	Overhead	2.5% to 13.8%	1%	1997
	RTMS	Overhead	2%	7.9%	1997
	RTMS	Sidefire	5%	N/A	1997
	RTMS	Sidefire	3% to 5%	N/A	2002
	RTMS	Sidefire	3%	N/A	1999
	RTMS	Sidefire	2.4% to 13.6%	2.6% to 5.9%	2002
Ultrasonic	TC 30	Overhead	2%	N/A	1997
	Lane King	Overhead	1.2%	N/A	1997
Passive Acoustic	SAS-I	Sidefire	8% to 16%	4.8% to 6.3%	2002
	SAS-I	Sidefire	4.0% to 6.8%	3.4% to 4.8%	2002
	SAS-I	Sidefire	10%	µ: -0.5 mph 4.8 mph	2000
	Smartsonic TSS-1	Overhead	4%	N/A	1997
	Smartsonic TSS-1	Overhead	15%	4 mph	2000
Video Image	Autoscope 2004	Sidefire	5%	5 mph	1999
	Autoscope 2004	Overhead	2.2% to 10.6%	N/A	1997
	Autoscope Solo	Sidefire	5%	8%	2002
	Autoscope Solo	Overhead	5%	2.5% to 7%	2002
	Autoscope Solo	Sidefire	2.1% to 3.5%	0.8% to 3.1%	2002
	VideoTrak 900	Overhead	1.6% to 4.8%	N/A	1997
	VideoTrak 900	Sidefire	10%	µ: +1.4	2000
	Traficon	Sidefire	5% (45 ft.) and 10% to 15% (25 to 30 ft.)	2% to 12%	2002

Table 9: Error Rates of Detector Devices in Freeway Field Tests (continued)

Technology	Sensor	Mounting Location	Accuracy Performance		Study Year
			Counts	Speed	
	Traficon	Overhead	2.7% to 4.4%	3% to 7.2%	2002
	Traffic Vision	N/A	1.8% to 4.8%	N/A	2000

Another similar study was performed in 2007 by the Arizona DOT: "State of the Art Evaluation of Traffic Detection and Monitoring Systems" (Figure 5, number 10). It includes a state-of-the-practice review of detection technologies used in Arizona (inductive loops and passive acoustic detectors), and the identification of the most promising technologies to meet the local needs. From the search, the authors noted that: "None of the analyzed non-intrusive detectors appear to be as accurate as loops under all environmental conditions but many agencies have determined that other positive features outweigh the modest reduction in accuracy. The technologies that have the most promise for replacing inductive loops at the time of the study were microwave radar, video imaging, and magnetic detectors" (*34*).

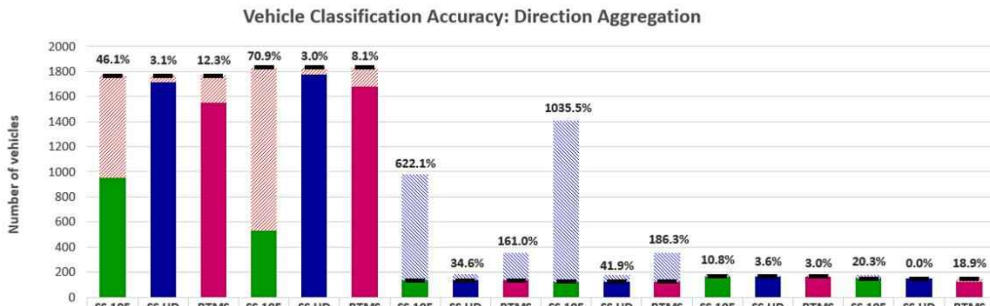
In 2009 the North Dakota DOT performed a study to determine the applicability of using radar-based traffic detection devices in the state (Figure 5, number 11). The following devices were tested for speed, volume, and classification accuracy: Wavetronix SmartSensor 105 (SS 105), Wavetronix SmartSensor HD 125 (SS HD) and RTMS from Electronic Integrated Systems (EIS). The ground truth for volume and classification was set through manual counts aided by video recording of the sample of interest. For speeds, the ground truth was obtained from handheld radar guns. Table 10 summarizes the findings.

Table 10: Sensor Volume Data: Error Comparison

Source: (*35*)

	SS 105	SS HD	RTMS
Disaggregated (Lane by Lane)	-8.5% to 30.7%	-2.6% to 4.5%	-10.4% to 26.1%
Direction Aggregation (Northbound and Southbound)	-0.3% to 6.1%	-0.6% to 0.9%	-1.4% to 3.0%
Total Aggregation (Total Volume)	0.6% to 4.0%	-0.3% to 0.2%	-0.8% to 0.8%

Overall, the SS HD was the most accurate for vehicle volume, slightly differing from the ground truth, as shown in Table 10 below. When the sensor data are aggregated, either by direction or total volume, the overall accuracy is improved mainly due to under and overcounts balancing out. Despite the fact that the SS HD was considered the most accurate, the researchers noted that the SS HD malfunctioned during one day of sampling and had to be restarted. The data for that particular day were not considered in the comparison. Regarding speed, the research demonstrated that both Wavetronix sensors had similar and realistic speed data, while the RTMS data were significantly different. When compared to the hand-held radar, the RTMS consistently reported higher speeds for closer lanes and lower speeds for distant lanes. The SS HD was the most accurate sensor, being within two to three mph of the hand-held radar. The researchers adopted three bins for the classification accuracy study: Small Vehicles (0 to 20 ft.), Medium Vehicles (20 to 55 ft.), and Large Vehicles (over 55 ft.). The SS 105 was the least accurate, presenting severe degradation in performance, undercounting small vehicles, and overcounting medium vehicles. The RTMS and SS HD presented the same pattern but with smaller degradation in performance. Figure 7 summarizes the classification accuracy results found in the research.



	Small Vehicles						Medium Vehicles						Large Vehicles					
	NB			SB			NB			SB			NB			SB		
	SS 105	SS HD	RTMS	SS 105	SS HD	RTMS	SS 105	SS HD	RTMS	SS 105	SS HD	RTMS	SS 105	SS HD	RTMS	SS 105	SS HD	RTMS
Overcounts	0	0	0	0	0	0	846	47	219	1284	52	231	18	6	5	30	0	0
Undercounts	815	54	217	1298	55	149	0	0	0	0	0	0	0	0	0	0	0	28
Accurate Detections	951	1712	1549	533	1776	1682	136	136	136	124	124	124	166	166	166	148	148	120
Target	1766	1766	1766	1831	1831	1831	136	136	136	124	124	124	166	166	166	148	148	148
% error	46.1%	3.1%	12.3%	70.9%	3.0%	8.1%	622.1%	34.6%	161.0%	1035.5%	41.9%	186.3%	10.8%	3.6%	3.0%	20.3%	0.0%	18.9%

Figure 7: Vehicle Classification Accuracy: Direction Aggregation

Adapted from: (*35*)

The study concluded that the SS HD from Wavetronix demonstrated the best performance, followed by the RTMS from EIS, both outperforming the SS 105 from Wavetronix (*35*).

In 2014, the Washington State DOT conducted a study intending to provide insight for transportation agencies in selecting devices for travel time estimation (Figure 5, number 12). The study presents an overview of the most prominent available technologies through field test evaluation of accuracy and reliability and also considering the cost of the systems.

The study was performed in two test sites. The first one was characterized by heavy daily traffic with frequent accidents, making travel times hard to predict. The second test site was a rural freeway. The upside of the first test site is the already installed Automatic License Plate reader, capable of storing a passing vehicle license plate to later match it with the next sensor location, providing that way accurate ground truth. The sensors being analyzed were the TrafficCast BlueTOAD, the Blip Systems BlipTrack sensor, the Sensys emplacements and Inrix. The TrafficCast BlueTOAD and the BlipTrack sensor rely on reading Media Access Control (MAC) address of electronic devices, the Sensys attempts to match the magnetic signature of each vehicle and the Inrix is based on cellphone and GPS data readings. To analyze the data, the study used mean absolute deviations to understand the magnitude of the error, mean percent error to verify biases, mean absolute percent error to find relative magnitude of the error and root mean square error to understand whether there are a few large errors or many small errors.

The study showed that the BlueTOAD and the BlipTrack sensors maintained the expected accuracy most of the time, with the exception of overnight hours when sampling is low. Some spikes during peak hours were also noted. The Sensys sensor generally reported satisfactory results. The Inrix sensor was the least responsible to traffic changes. In general, the systems had flaws in detecting road closure. The authors mention that each system had strengths and weaknesses that should be analyzed and considered, additionally to accuracy and sample rates (*36*).

3 State of the Practice

This section presents a summary of the practice for selected FDOT districts on vehicle detection technologies currently in use, their failure modes, maintenance practices, verification tests, and application-specific tests. Several districts ITS engineers and maintenance personnel were interviewed to obtain a general idea of VDS accuracy, consistency, and performance over time.

3.1 Systems Engineering View of VDS Deployment Process

Traffic monitoring is one of the core functions in a traffic management center (TMC). It requires reliable traffic sensing equipment and communication links. Intelligent Transportation Systems (ITS) usually cover the aspects of monitoring, communication, and traffic/incident management. ITS design and deployment have a well-established systems engineering (SE) process that has been continuously applied for several years. This maturity allows the generalization of a high-level system architecture and implementation packages. Agencies can select these high-level architectural elements and develop regional deployment plans. Additional information of the systems engineering process for ITS systems can be found in (*37*). In Florida, the implementation of the ITS architecture is executed by the SunGuide® system software. As observed in Figure 8 the traffic detection function is at the core of the architecture and is allocated to the Traffic Sensor Subsystem (TSS).

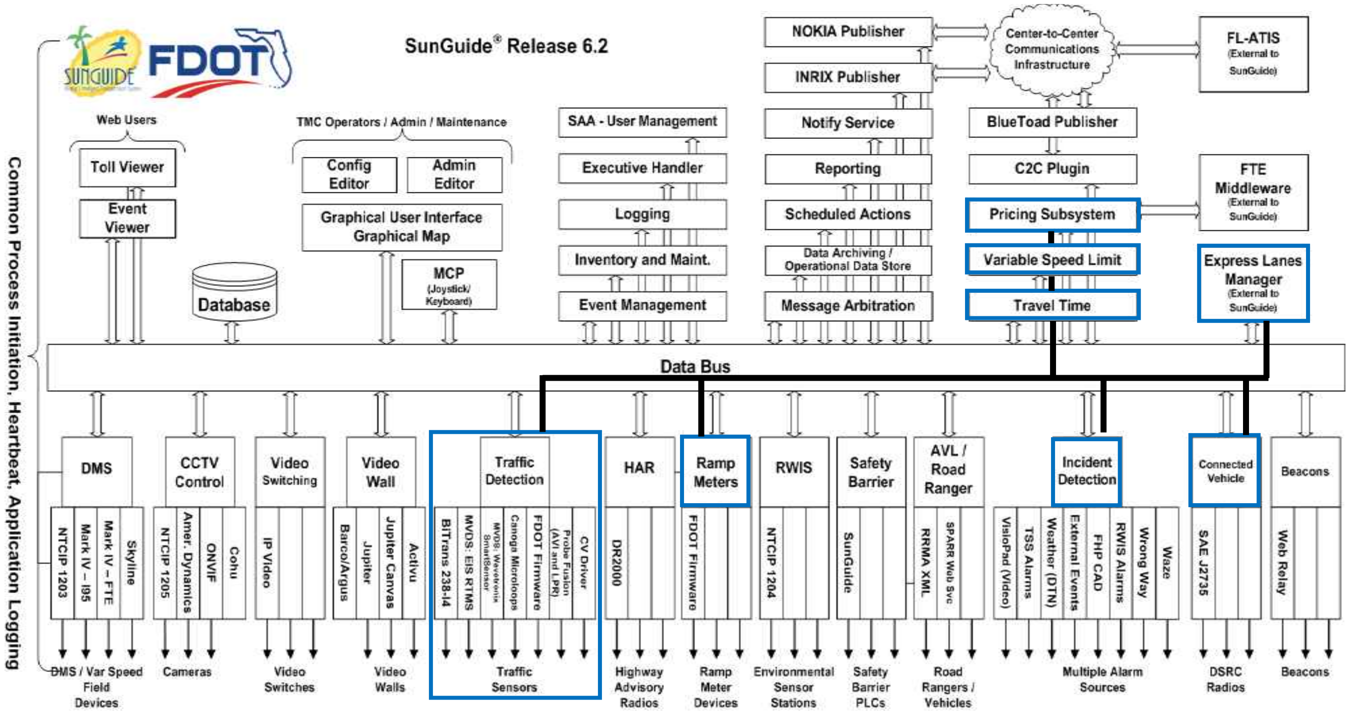


Figure 8: SunGuide Architecture, Traffic Detection Function, and TMC Applications

The TSS provides granular vehicle detector data in time and space for the TMC applications. These applications may further process the TSS data aggregating it over a specified segment or at predetermined time intervals based on their objectives. Examples of applications include travel time posting, variable speed limits, and express lanes among others. In the near future, connected vehicles may receive data generated by the TSS, processed, and transformed by the TMC via infrastructure to vehicle communication interface. TSS may be required event with increased market penetration rate of connected vehicles as an agency-side mean to verify traffic conditions parameters. In addition, vehicle detection systems will play an important role in verifying the presence of connected vehicles to provide enhanced level of data validity and security.

The more granular data collection functions of traffic detection requirements can be allocated to individual VDS. These VDS may be of one of several technologies such as microwave, video, magnetic, and acoustic. For each of these technologies, there are several manufacturers/vendors which gives a wide range of product availability. To ensure operational compatibility, FDOT-TERL elicits, maintains, and publishes the general requirements for VDS equipment for use in Florida. These requirements involve hardware/software capabilities for the VDS and provide guidance on measurement and testing procedures. For a VDS to be deployed in Florida, it needs to be on the FDOT Approved Product List (APL). Specification 660, Vehicle Detection Systems (*38*), sets the procedure and required testing, performance targets, and applicable standards for a VDS to be included in the APL. These requirements also serve as the basis to derive or refine additional requirements that are allocated during later stages in the development process of ITS applications. These requirements are used as guidance by local agencies and applied to operation and maintenance at later stages in the lifecycle of an ITS application.

Figure 9 presents an overview of the systems engineering process or "vee" diagram as it applies to ITS deployment projects. Agencies select the elements or applications to be deployed from the regional architecture. This selection can include electronic toll collection, managed lanes, ramp metering among other TMC applications. The plans are studied and then developed into a concept of operations (ConOps) where the stakeholders are involved and the selected architecture elements are adapted to the local needs and goals. Once the ConOps has been approved, the ITS deployment goes to the design phases where all the layouts and site plans are developed. At the bottom of the diagram is the implementation/acquisition phase during which agencies select the specific VDS devices to install for their projects. The selected devices shall be in conformance with the functional and performance requirements for integration with existing ITS systems. The FDOT TERL acts as a quality assurance entity by reviewing the elements and application of the regional architecture (Figure 9, flow 1) and eliciting (establishing) functional and performance requirements for VDS providers (Figure 9, flow 3). The quality assurance is done by maintaining FDOT Specifications 660 (see Figure 9 flows 3, 4). VDS devices satisfying specification 660 become part of the APL and can be procured and used for traffic control and monitoring applications (see Figure 9, flows 2 and 5).

One of the objectives of FDOT Specifications 660 is to set provisions for the installation of traffic detection systems that provide accurate, consistent, and reliable data to the consuming applications. The Specification covers several aspects such as materials, testing, and compliance with industry standards. The quality of the implementation (satisfaction) of the VDS requirements is verified through tests and procedures at the deployment stage (see Figure 9, flows 6 and 7). These objectives, and the corresponding verification procedures are also propagated to operational phases of the system to ensure continued data quality (see Figure 9, flow 9). Once the VDS is in operation, maintenance acceptance tests should ensure that accuracy, consistency, and reliability objectives are met over time. Figure 9, flow 8 reflects application-specific requirements for VDS. These application-based verification requirements need to be carefully devised to maintain the overall system performance at operational levels.

Verification tests for new VDS installations and maintenance work acceptance are derived from the same guiding specifications (Specification 660) but adapted differently by each jurisdiction. Special characteristics of the underlying TMC applications may influence the way VDS devices are monitored for accuracy, consistency, and reliability.

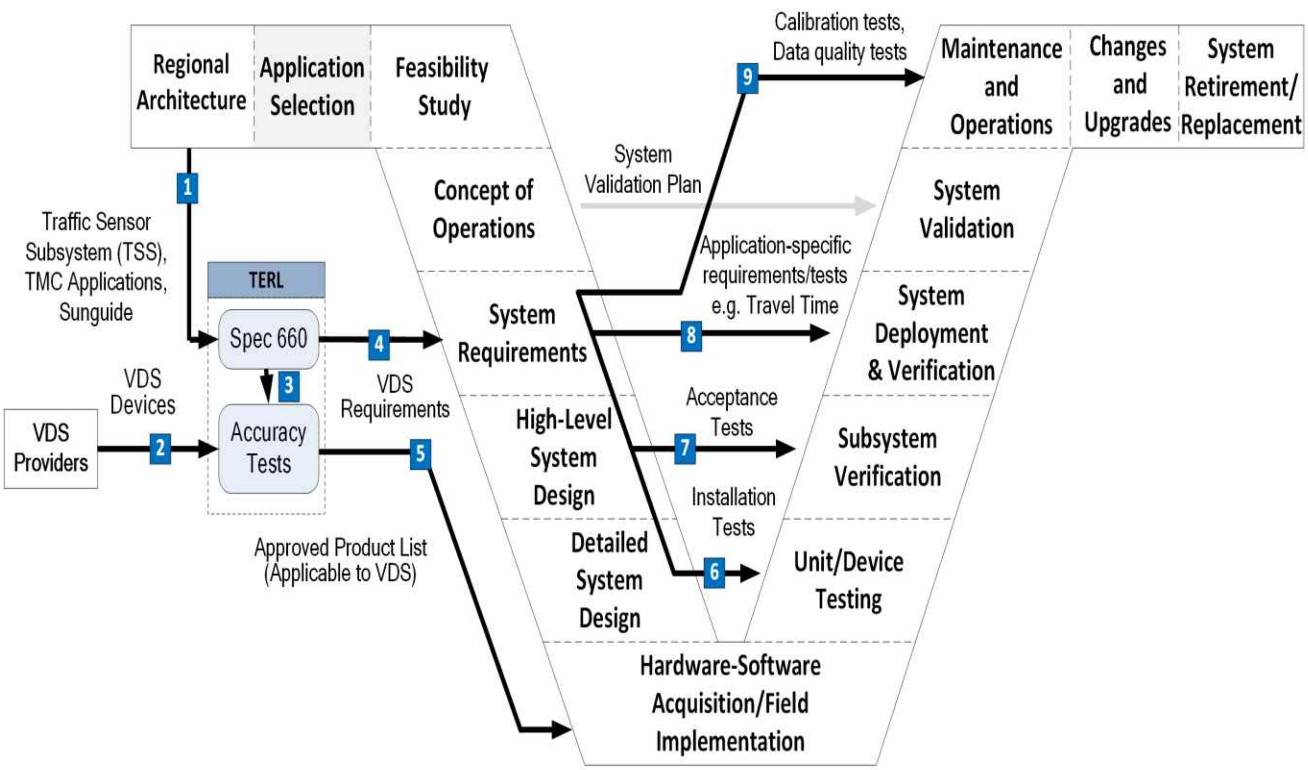


Figure 9: Role of VDS Requirements in the ITS Systems Engineering Process

The next section presents a summary of the state of the practice on requirements for VDS system and provides recommendations for requirements management and verification. It is then followed by a summary of the state of the practice of VDS technologies, installation tests, and lessons learned from selected FDOT districts.

3.2 Current Experiences with Deployed VDS

Detector issues and maintenance practices were collected and compiled from several districts in Florida. This section presents a summary of the key findings of this task.

3.2.1 District 1

FDOT District 1 is formed by 12 counties spanning 1,870 state highway center miles. Interstate I-75 is the main freeway in the District. A summary of the District's experience deployed VDS is provided below.

3.2.1.1 Detection Technologies in Use

The traffic monitoring system currently deployed in FDOT District 1 (FDOT D1) comprises VDS equipment using microwave technology. The VDS models are ISS-X3, ISS-G4, Wavetronix SS-105 and Wavetronix SS-125 HD. In 2015, FDOT D1 performed a study at selected sites to verify accuracy performance on selected VDS from each manufacturer. The study found that there are several factors influencing detector performance causing them to require periodic recalibration. These causes are summarized in the next section.

3.2.1.2 Causes of VDS Failures

FDOT D1 conducted a study on detector performance on 12 detectors located in Collier, Lee, and Charlotte counties on Interstate I-75. The study found that the main causes of variation observed in the VDS inspected sample are:

- Attachment method used,
- Vibration of the pole,
- Environmental effects on the alignment of the detector, and
- Frequency drift.

For VDS data accuracy loss modes, it was reported that volume or undercount was observed due to occluded vehicles by high profile trucks or in the proximity of barriers.

3.2.1.3 Maintenance Practices

FDOT D1 calibrates the MVDS detectors quarterly. Calibration is performed and evaluated by field tests for accuracy for volume and speed. The field test consists of collecting volume data and speed data on 10-minute intervals.

3.2.1.4 Additional Findings and Lessons Learned

The study conducted by FDOT D1 reported the following additional findings and recommendations which are summarized as follows:

- Timestamps between the detectors and SunGuide presented inconsistencies.

- Synchronization between SunGuide and detector is necessary to compare detector memory data and data retrieved at the TMC versus ground truth data collected in the field by installers.
- Non-synchronized data comparisons aggregated over short period of time are likely to present discrepancies. These discrepancies are reduced when data are aggregated over longer periods, which tend to be more accurate.
- In their assessment, District 1 found that only one out of a sample of twelve inspected MVDS passed the performance tests for speed and volume accuracy.

3.2.1.5 Cause and Effect Diagram for District 1

Based on FDOT District 1 experience with VDS, the cause and effect (fishbone) diagram in Figure 10 was used to provide a visual summary of main detector issues. A description of the fishbone diagram is also included below to explain the usage of the diagram.

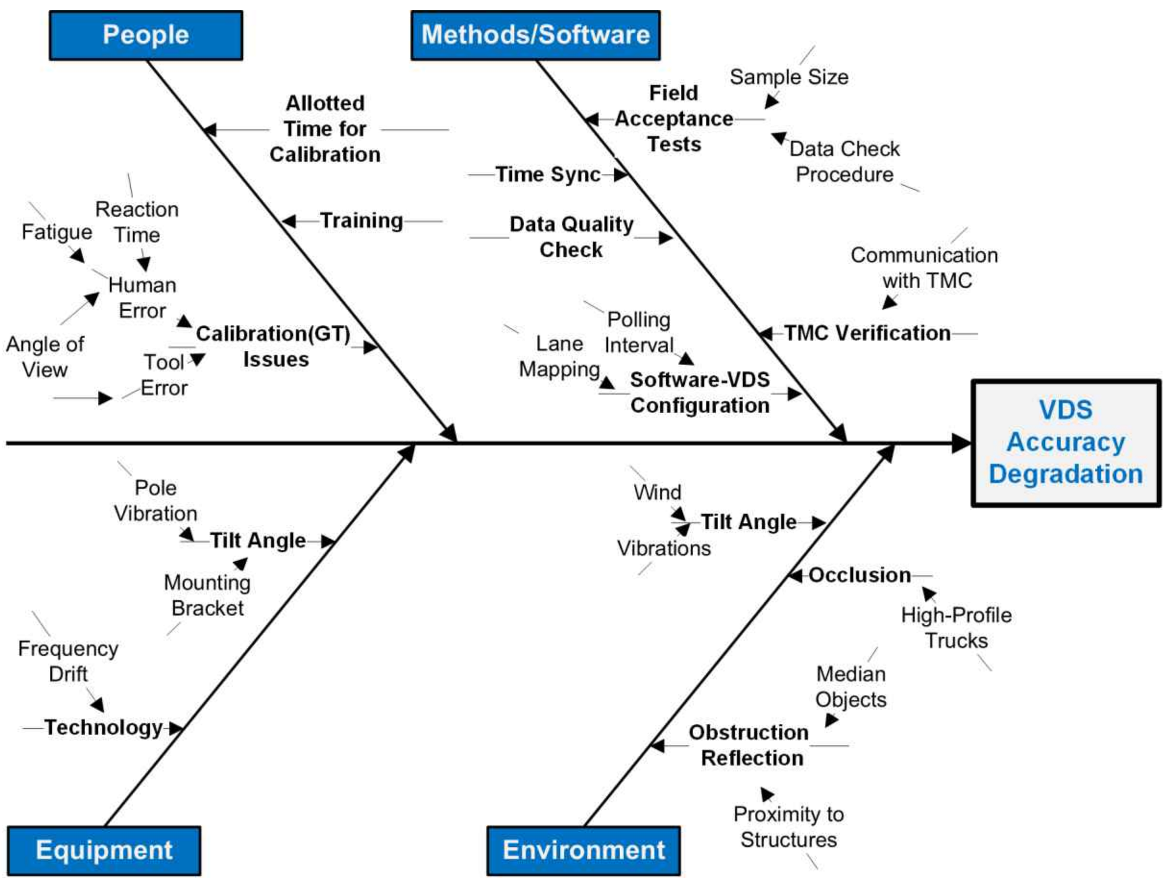


Figure 10: Cause and Effect Diagram for FDOT District 1

The cause-effect diagram includes a series of reported causes in the categories of Methods, Measurement, Verification and Validation, Hardware, Software, and Environment. Each category has an associated effect and a cause which is considered the root cause under the specified category. For example, in Figure 10, the method of attachment influences the tilt angle causing degradation in the accuracy, consistency, and reliability of VDS. Also, it can be observed that equipment or hardware failures include mounting bracket and pole vibrations that modify the tilt angle of the detector contributing to accuracy, consistency, and reliability (ACR) degradation. Likewise, equipment software features such as time synchronization can present issues in the overall performance of the detector. The greyed-out sections of the cause-effect diagram correspond to the overall objective of this project: to evaluate and revise the methods and performance specifications for VDS.

3.2.2 District 2

FDOT District 2 consists of 18 counties comprising 2,556 centerline miles of state highways. Interstates I-75 and I-10 are the main Freeways traversing District 2. The District also has the Interstate I-295 that serves as an auxiliary route of Interstate I-95 around the city of Jacksonville.

3.2.2.1 Detection Technologies in Use

Side-fire microwave detectors were adopted as the main technology to support operations. A demonstration was requested form several vendors. Several aspects of MVDS performance were evaluated including installation procedure, calibration, accuracy, and reliability. While MVDS's are relatively simple to install, calibration, and reliability were differentiating factors among the selected providers. Currently, there is a mix of manufacturers and models. Manufacturers include Wavetronix and Image Sensing Systems. For each manufacturer there are different models varying form average performance to the most high-performance technologies. This variation is due to the types of contracts applied to ITS deployments (e.g., low bid contracts). Microwave detectors in use are Wavetronix (model SS-105, SS-125, SS-126) and ISS (RTMS-G4, RTMS -SX-300). Applications currently supported by the deployed VDS include travel time posting, incident detection, performance monitoring

3.2.2.2 Causes of VDS Failures

Gateway devices (device server) used convert VDS interfaces (e.g., RS-232, RS -485) to Ethernet for data transfer may fail more frequently than the VDS itself. This is mainly due to power surges due to storms or power distribution network.

Low-density and high speed such as night time/early morning presented accuracy and consistency issues in VDS data. In some cases, average speeds were observed lower than expected for low-density conditions. MVDS accuracy degrades during high-occupancy low speed conditions such as in peak hours in highly populated urban areas.

Lane/configuration drifting was also reported as a failure mode. For some models, initial configuration is lost with time for no assignable cause.

3.2.2.3 Maintenance Practices

FDTO District 2 conducts a semi-annual probe vehicle speed and travel time test. During the test the maintenance personnel find the most inaccurate device in a segment for maintenance. Probe vehicle and 3rd party data (e.g., INRIX) are used to test accuracy performance of Bluetooth devices

For new equipment installations of MVDS are required to avoid when possible metal structures. However, software improvements have made installation and calibration more robust. For the installation procedure the technician installer adjust the MVDS head and perform initial calibration. When passed, the head is locked in position. TMC operators and field installer perform a join verification of MVDS operation (e.g., lane mappings).

3.2.2.4 Additional Findings and Lessons Learned

Additional findings and lessons learned from FDOT District 2 include:

- Video detection was tested in the past. It was found that performance fluctuated based on environmental factors such as glare from sun and rain. Video detection did not offer a consistent source of traffic data to support TMC applications.
- License plate recognition was implemented but retired due to inaccurate readings and maintenance load.
- Bluetooth was deployed in the field about 140 detection points. Bluetooth data are combined with VDS data to provide origin-destination analyses.
- Wrong way detection could not be implemented due to VDS accuracy out of the required value (100%).
- For express lanes currently the used density is between 1/3 to ½ miles per detector
- Traffic signals some jurisdictions are experiencing problems with video detection (site-specific based on time of the day) and are starting to use microwave for presence detection (Wavetronix matrix).
- Polling cycle in use is 20 seconds.
- For high-density urban areas the Wavetronix HD is currently the preferred alternative.
- An infrared camera is under testing for incident detection on low speed high occupancy scenarios.

3.2.2.5 Cause and Effect Diagram for District 2

The experience of FDOT District 2 with MVDS is summarized in Figure 11. There are two traffic conditions that may affect the accuracy of the MVDS. Also proximity to structures was listed a possible contributing factor. FDOT District 2 promotes the communication between the TMC and the installer in the field to prevent configuration errors. However when configuration is lost, may be due to the software of the device. Reliability of communication equipment was also found to influence the uptime of the system. Installation methods also can play a role in the accuracy of the equipment, especially if the MVDS calibration require more manipulation of parameters and settings.

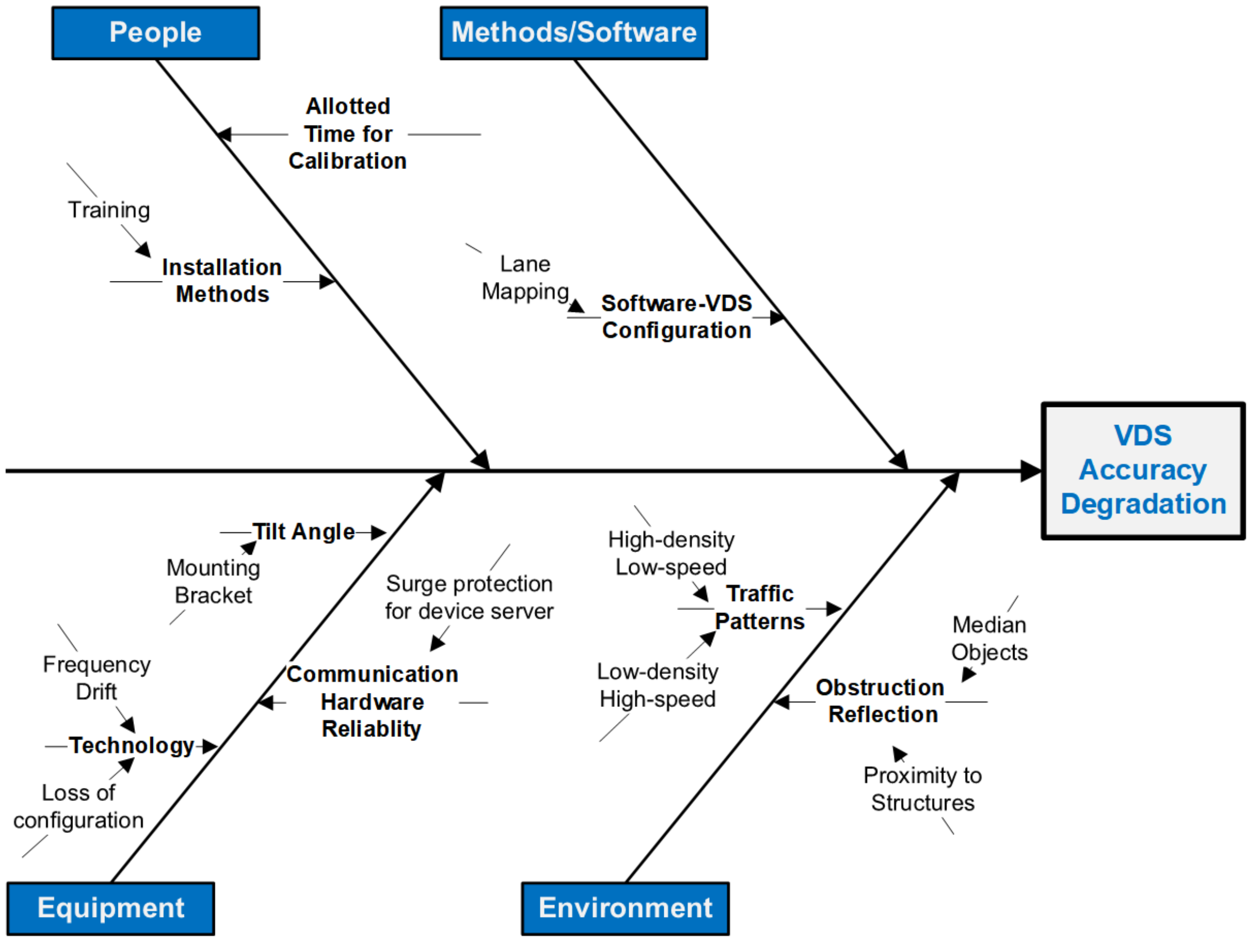


Figure 11: Cause and Effect Diagram for FDOT District 2

3.2.3 District 4

District 4 is located on the East Coast of Florida covering five counties spanning 1,385 center miles of state highways. District 4 is in the starting phase of the implementation of a managed lanes application on the I-95 interstate. This application is an extension of the I-95 express lanes in District 6.

3.2.3.1 Detection Technologies in Use

FDOT District 4 currently uses microwave detectors as their main source for traffic monitoring data. All of the detectors used for freeway monitoring are from Wavetronix. Most of them are the model 105 with over 10 years in the field. District 4 is currently in the process of upgrading their systems to the Wavetronix HD model. There are over 400 detectors currently employed in District 4 in the I-95 corridor. No physical degradation of the equipment has been observed including the older detectors.

3.2.3.2 Causes of VDS Failures

Lightning is the most frequent environmental cause of failure for detection equipment. District 4 experienced accuracy and consistency issues with detection systems during the initial deployment phase. After conducting a series of detailed experiments, data collection, and analysis, it was observed that the data coming out of the detector complied with the accuracy levels. However, errors were introduced when data were pulled from the detectors by the SunGuide system. Among the causes of error or inaccuracies between the observed and the reported traffic variables, discrepancies were found in reading from volatile memory versus reading from the non-volatile data buffer. The two main causes for these discrepancies were:

- Interval messaging in the detector not in sync with data polling interval from SunGuide
- Inconsistent lane numbering in some roadway segments

Communication failures also affect the reliability of the detection equipment. Currently Wavetronix does not provide communication terminals for their equipment. The detectors are not IP-addressable and hence need a communication terminal for data transfer. The communication components fail with higher frequency than the detectors. This causes apparent detector failures, but these are ultimately communication failures.

3.2.3.3 Maintenance Practices

FDOT District 4 developed its own calibration procedure to check detector maintenance work orders (acceptance test). In the TMC organizational structure, District 4 created a position designated as Assistant Managed Lanes Coordinator whose function includes detection status verification, detector troubleshooting, new installation approval, and maintenance work on VDSs, especially those assigned to managed lanes.

3.2.3.4 Additional Findings and Lessons Learned

FDOT District 4 developed a special tolling software that reads data directly from a redundant serial port in the communication terminal of the detector, bypassing the SunGuide data retrieval process. It was reported that in the developed application, there are no discrepancies between the data that come out of the detector and the data that are used by the tolling software. Furthermore, the accuracy of the detector is within the limits specified in the APL and in accordance with vendor specifications.

Currently, there is no formal procedure to automatically detect data quality or accuracy errors (drifting, undercounting, etc.). However, customized software scripts (in addition to the tolling software) are run to check for evident errors such as excessive speeds (e.g., 300 mph). It was noted that such excessive speeds are not filtered by SunGuide and are archived in the data warehouse.

Surveillance cameras are monitored using video analytics from the software application Citilog. This helps TMC personnel to perform their work efficiently.

At earlier stages of implementation of the travel time posting applications, there were discrepancies between the posted travel times and the actual travel times for uncongested conditions. Detailed review showed that segment lengths for travel time segments were incorrectly set up in the travel time calculation application.

It was noted that because of data inaccuracies due to diverse causes, a significant portion of volume and speed data from the data archives in the last 10 years cannot be fully trusted. In addition, count data from the ITS infrastructure cannot be used for planning applications due to severe inaccuracies in some segments. This causes additional costs since the data need to be collected by independent contractors.

Currently FDOT District 4 runs two systems (SunGuide and D4's tolling software) in order to successfully carry out the express lanes application. However, it was noted that recent efforts by the SunGuide development team have improved the data retrieval for detector data but some issues remain unsolved.

In addition, FDOT District 4 developed in-house validation tests to be executed on the TMC side by an operator to validate or troubleshoot a VDS. The application was developed using the Python programming language and compares the volumes generated by the VDS with volumes collected by the TMC operator using CCTV.

3.2.3.5 Cause and Effect Diagram for District 4

A cause-effect diagram summarizing VDS experience for District 4 is presented in Figure 12. It can be observed that communication failures are the main equipment-related failure reported. Other aspects are related to data handling such as synchronization and incorrect lane mapping.

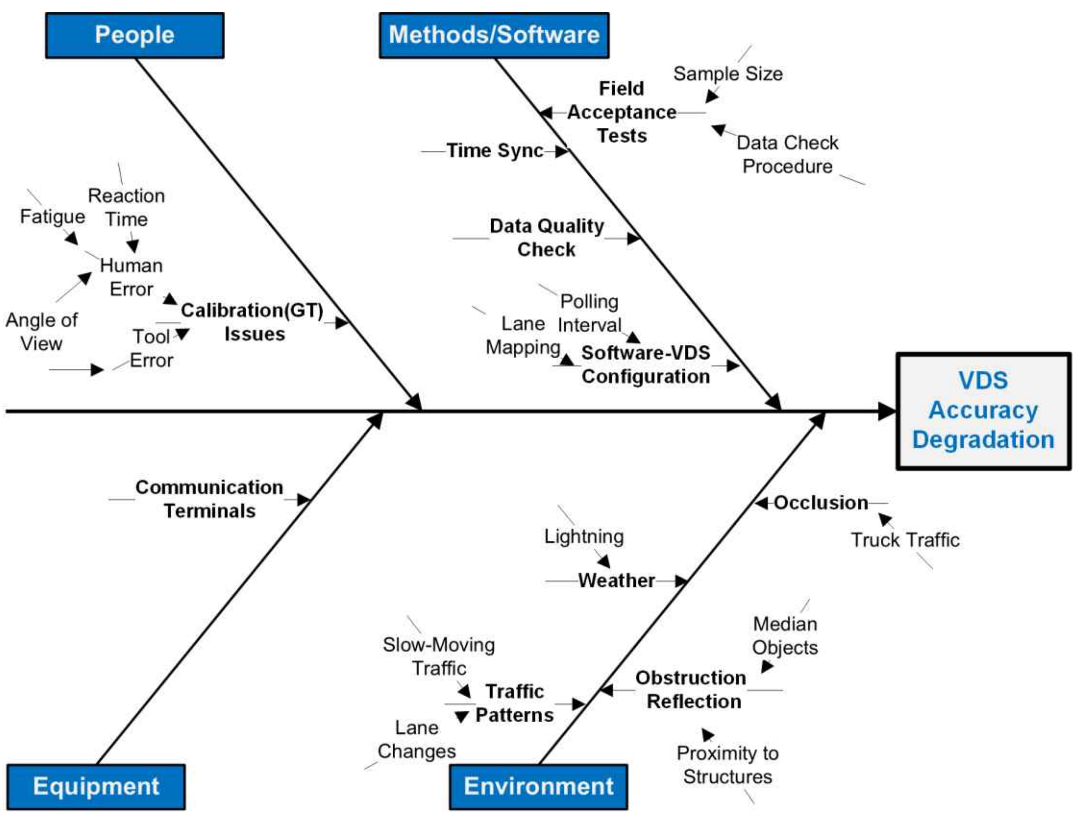


Figure 12: Cause and Effect Diagram for FDOT District 4

3.2.4 District 5

District 5 is located in Central Florida comprising nine counties. It spans 2,124 of state highway centerline miles. The main freeway is Interstate I-4. District 5 also contains toll roads such as SR-417 and SR-408 among others.

3.2.4.1 Detection Technologies in Use

District 5 currently uses loops and microwave detectors for traffic monitoring. A few loops remain operational (about 72). In general, inductive loops have been replaced by non-intrusive vehicle detection technologies such as microwave.

Most of the microwave detectors are Wavetronix (model SS-105, SS-125, and SS-126). There is a small proportion of ISS-G4 MVDS. Currently, there are nearly 300 detectors in the field. The majority of Wavetronix detectors are of the 105 model and have reached the end of the useful life (i.e., 12 years). No significant physical degradation was observed in the equipment

In District 5 urban areas, detectors are places every ½ mile. For rural applications, detectors are placed every one mile.

3.2.4.2 Causes of VDS Failures

District 5 microwave detectors start to have inaccuracies for speeds below 35-40 MPH. It has been observed that microwave detectors have higher accuracy for speed and less accuracy for volume. The general behavior observed for traffic volumes was a downward trend. This causes the reported traffic volumes from the detectors to be lower than the actual volume (underestimation).

Some of the sources for detector inaccuracies are due to installation procedures. For microwave detectors, these factors include locations with occlusion, backscatter, or incorrect placement so that the detector does not capture far-side traffic data. For loops, the sources of detector inaccuracies include installation/repair errors (e.g., loop wiring errors, incorrect sealing of the saw cut). Installation on concrete roadways limits the number of repairs that can be performed on loop detectors affecting their service life when compared to asphalt roads.

Newer models for microwave detectors present good accuracy at approximately 25 MPH. However, below 25 MPH the detectors tend to undercount vehicles.

3.2.4.3 Maintenance Practices

Detectors are maintained quarterly (preventive maintenance) or on demand if a failure is detected. A non-operational detector is the most evident failure mode that triggers a maintenance visit. Other failure modes need to be of extreme nature to be detected (e.g., extreme values of speed such as 600 mph).

3.2.4.4 Additional Findings and Lessons Learned

Based on the experience and applications of VDS systems, District 5 ITS engineers suggested that the acceptance criteria need to be more stringent when the data are needed for realistic operating conditions for TMC applications. For example, obtain an accuracy of 95% when speeds are 10 MPH.

Applications such as variable speed limits were discontinued due to lack of compliance from the public. It was suggested that speed limits are changed based on safety related issues (e.g., weather). For congestion management applications the compliance rate was very low.

Overhead cameras for express lanes is an option currently being explored. Cameras on roadside poles may not be a viable solution due to occlusion problems. Occlusion problems can be avoided by using a high pole but this will require the use of special bucket trucks (standard bucket truck reach is 40 ft.) or camera lowering devices resulting in excessive costs.

It was suggested that there may not be a single technology that is dominant for all the applications. For example, loops are more suitable for asphalt roads with minimum truck traffic, while for express lanes overhead cameras may be the best solution. For general speed monitoring, side fire microwave may be more suitable. Future applications that require operational vehicle detection system include, managed lanes, ramp metering, and hard shoulder running. Applications that will benefit from accurate detection are planning, incident detection, and arterial management.

3.2.4.5 Cause and Effect Diagram for District 5

Figure 13 presents a cause-effect diagram for District 5. Incorrect setup is one of the listed causes of detector malfunction. For hardware, degradation effect due to equipment aging was the main reported cause of VDS failure. Some of the VDS weaknesses were addressed with the acquisition of newer detectors since, in general, their technology has not been upgraded in the last 10 years.

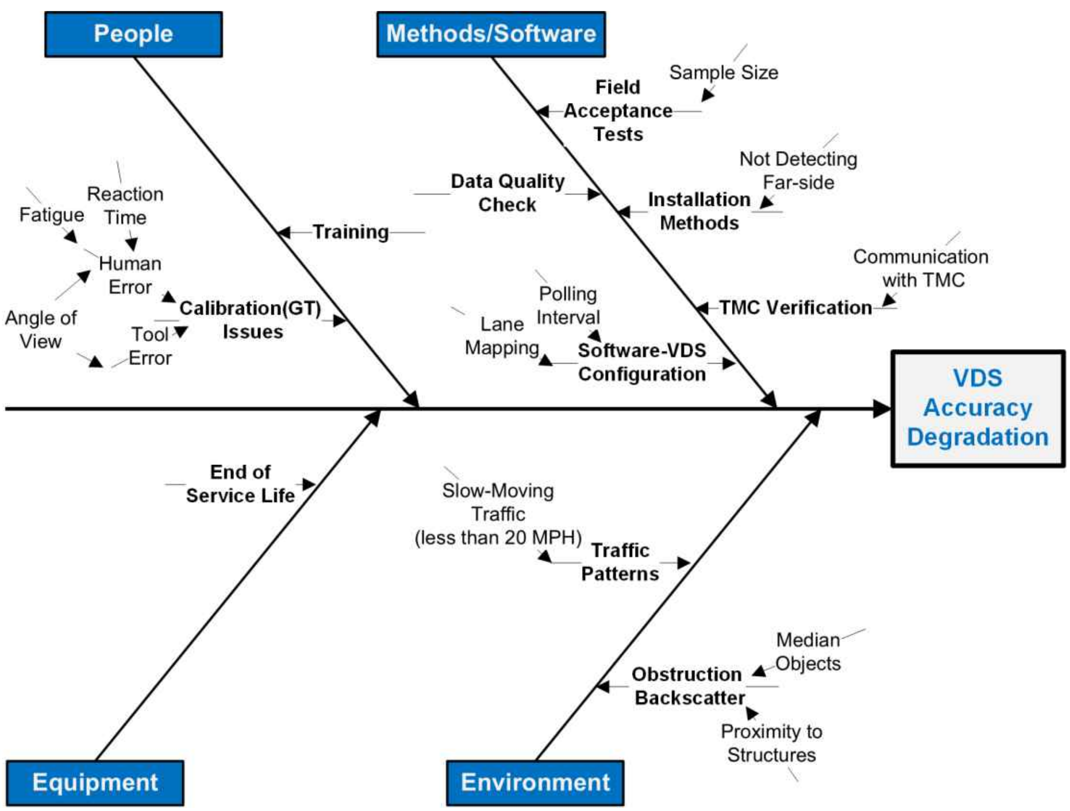


Figure 13: Cause and Effect Diagram for FDOT District 5

3.2.5 District 6

District 6 comprises two counties Miami and Monroe and is located in the southern part of Florida spanning nearly 700 centerline miles of state highways. Interstates I-95 and I-75 are national freeways that originate in this District and extend to several other states. District 6 has pioneered several ITS applications such as ramp metering and managed lanes in Florida.

3.2.5.1 Detection Technologies in Use

District 6 originally installed RTMS models X2 and X3 (ISS). These models are at the end of their service life and are being replaced. Currently, there is a mix of RTMS (ISS) and Wavetronix detectors in the District.

3.2.5.2 Causes of VDS Failures

Geometry is one of the main factors affecting accuracy. Median objects, noise attenuating walls and roadway infrastructure pose challenges on sensor placement. Work zones, contractors, landscapers can also affect the accuracy of detectors by placing large objects in the detection zone as part of their work. In some cases, construction or landscaping modifications are performed without taking into consideration the existing ITS infrastructure. This can lead to potential detector issues, and possible relocation of the detection equipment.

When a detector has consistent data issues, the event is escalated to the maintenance department. The maintenance department visits the site and performs recalibration of the detector.

It is suspected that temperature changes during the day may affect the accuracy of the detector. However, quantitative evidence is needed.

3.2.5.3 Maintenance Practices

Calibration for the express lanes is performed in segments bordering with the Florida's Turnpike. Ground truth data for entering/exiting volumes is taken from Toll gantries where multiple detection equipment are present. The assessment of the detection system is performed using an in-house algorithm.

There are two types of reliability measures used by FDOT District 6 to assess the status of the detection system. One is related to the detector status itself, and the other is related to the communication status. In doing it this way, communication failures are not attributed or masked as detector failures.

District 6 created a calibration procedure for detector setup and calibration. The calibration procedure is mainly focused on detectors ISS-X3 and ISS-G4 but it can be applicable to other microwave detectors as well. The calibration test is derived from the tests described in specification 660applying the minimum pass/fail criteria for speed and volume.

3.2.5.4 Additional Findings and Lessons Learned

Presence detection and queue detection are used for ramp signaling. Ramp signaling has a proprietary algorithm that uses a fuzzy logic-based controller. The algorithm is proprietary and cannot be accurately replicated. However, it was suggested that a simplified base algorithm/plan for ramp signaling may be simulated to reflect VDS accuracy degradation.

Ramp signaling uses Type 170 traffic controllers. In the past there were time drift issues between the controllers and SunGuide. This was mitigated in subsequent SunGuide upgrades.

3.2.5.5 Cause and Effect Diagram for District 6

Figure 14 presents a graphical summary of the reported experiences with VDS maintenance in District 6. The VDS aging process, for older models, and environment causes, such as roadway features, are the main causes for VDS degradation in accuracy and consistency. It is suspected that temperature may be related to inaccuracies during the day.

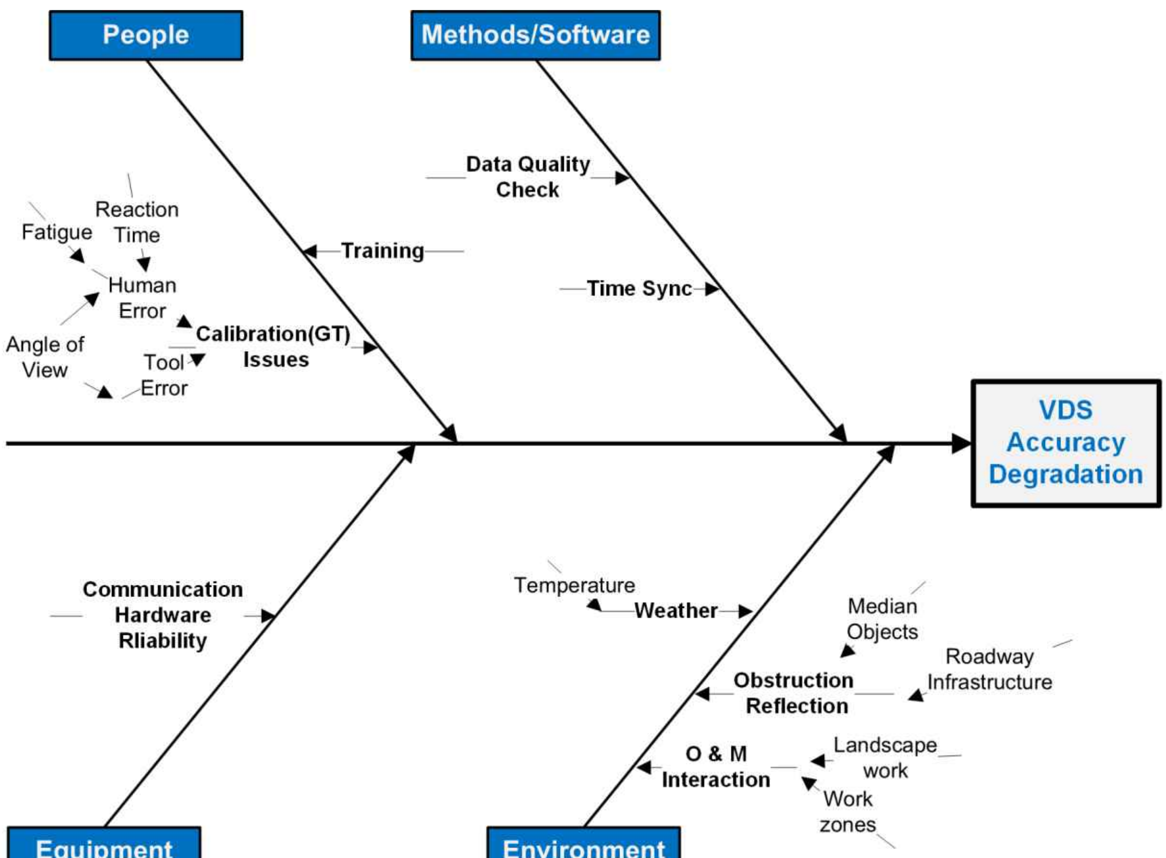


Figure 14: Cause and Effect Diagram for FDOT District 6

3.2.6 District 7

FDOT District 7 comprises seven counties with 1,064 state highway centerline miles. The District has several freeways such as Interstates I-75, I-4, and I-275. It also has several toll roads such as the Lee Roy Selmon Expressway.

3.2.6.1 Detection Technologies in Use

District 7 has 475 MVDS deployed along their interstate system. The VDS manufacturers are ISS X3, ISS-G4, Wavetronix SS-105 and Wavetronix SS-126 HD. Detectors are deployed every half mile in urban areas and every mile in rural areas.

3.2.6.2 Causes of VDS Failures

Based on information provided by TMC personnel in District 7 the following are the main observed causes of VDS failure:

- Heavy birds (e.g., brown pelicans) landing on the MVDS modifying tilt angle. This is associated with mounting bracket issues,
- Vibrations were also found to modify tilt angle,
- Plastic cover of antennas found degraded exposing critical components, and
- Waterproof seals being compromised causing water intrusion.

Other factors associated with weaknesses of the technology include:

- Reflection with proximity to structures (steel structures, median barriers),
- Failure to detect slow moving vehicles, high density situations, and
- Issues with large trucks (occlusion).

3.2.6.3 Maintenance Practices

Detectors are maintained once a year as regular preventive maintenance practice. On-demand detector maintenance is prioritized to a set of 63 strategic MVDS supporting performance measure reporting. The remaining detectors are maintained once a year or on demand if found non-responsive via system reports. Devices found to be non-operational are swapped for operational ones by the maintenance personnel. There is a significant amount of MVDS in stock as back up for faulty field MVDS.

The maintenance procedure includes: before calibration measurements (if the MVDS is found operative), adjustment and after calibration measurements. Both datasheets are attached to the maintenance log of the device. Detector maintenance test follow the test procedure used in FDOT District 6.

3.2.6.4 Additional Findings and Lessons Learned

MVDS were originally used to detect incidents based on speed measurements. Due to accuracy and consistency issues on the devices, the system gave a large number of false positives (system alarms). This was overwhelming for the TMC operators to verify. The application was eventually turned off and incident detection is performed via CCTV cameras by the operators

Short tests (less than one year) on accuracy and consistency are usually successful. Devices fail for multiple causes including degradation of the equipment due to environmental factors. Based on the experience with current MVDS equipment, FDOT D7 suggested increased frequency of test periods. It was also suggested to add specifications related to the long term integrity of the components of the device to ensure reliability of traffic monitoring systems.

For wrong-way detection applications, loops have been found to offer a more consistent output for accuracy and consistency. A mix of detection technologies coupled with video analytics are the candidate technologies for wrong way detection applications

Unsuccessful applications due to equipment unreliability include system wide performance measures and incident/queue detection. Currently supported MVDS applications include performance measure monitoring at selected corridors. Future applications (FY 2017) for FDOT District 7 include queue/incident detection, managed lanes, and ramp metering.

3.2.6.5 Cause and Effect Diagram for District 7

A graphical summary of VDS maintenance experience for District 7 is presented in Figure 15. It is observed that equipment degradation resulting in water intrusion has been observed. In addition, mounting bracket issues affecting the tilt angle of MVDS have been reported due to several causes. Among these causes are heavy birds landing on the detector and vibrations.

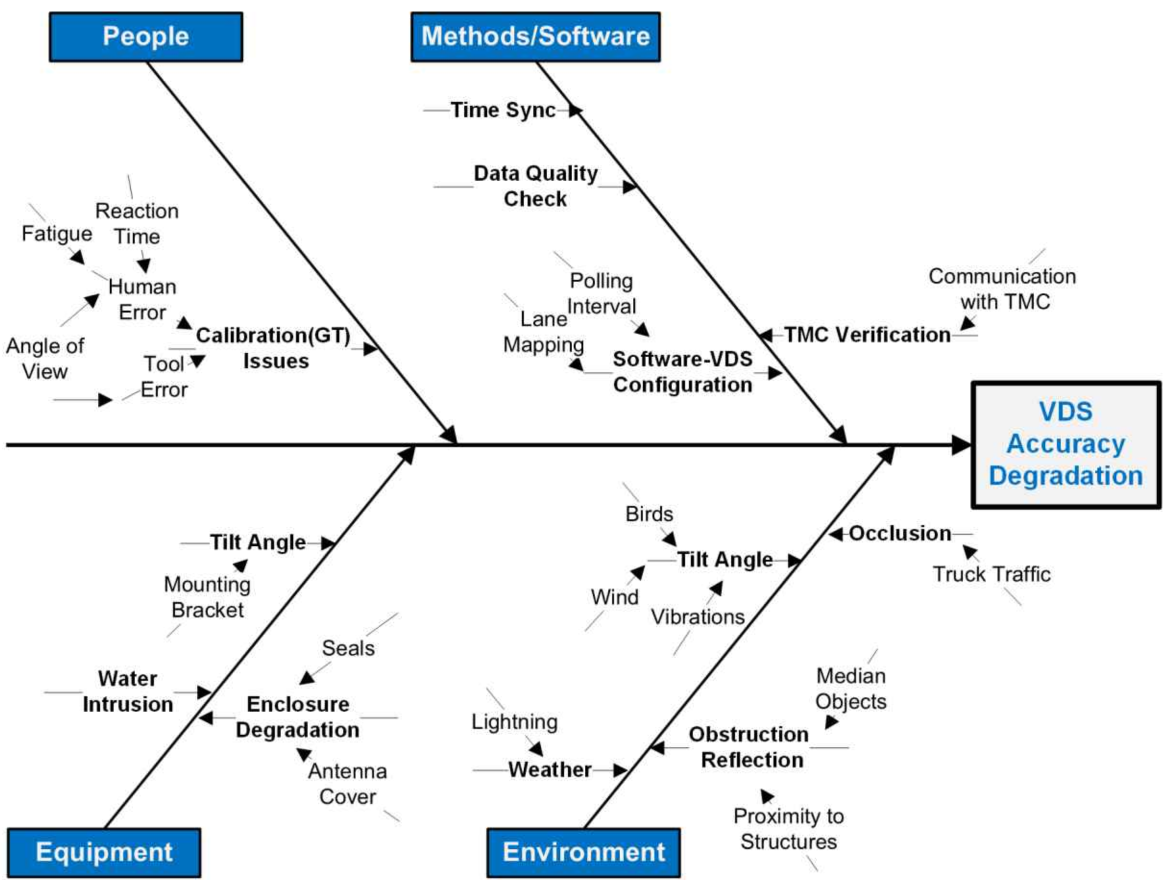


Figure 15: Cause and Effect Diagram for FDOT District 7

3.2.7 Florida Turnpike Enterprise

The Florida Turnpike Enterprise (FTE) spans nearly 500 center miles of roadway mainly located in South and Central Florida. The FTE consist of the mainline from Miami to Central Florida and additional toll segments such as Polk Parkway, Central Florida GreeneWay, among others.

3.2.7.1 Detection Technologies in Use

Side-fire microwave vehicle detection is the preferred form of detection for FTE applications. The FTE roadway monitoring system is supported by 1,100 MVDS. The MVDS in use are mainly Wavetronix having a mix of HD (SS-125, SS-126) and SS-105. A significant portion of the SS-105 detectors are at the end of the service life and are being replaced with HDs.

Mainly speed and volume are actively used by FTE. Other MVDS data collection capabilities such as classification is used on demand for special studies. Occupancy is rarely used as an application parameter, but it is used for data quality tests in SunGuide.

Applications using VDs data include Ramp closures, Dynamic pricing for express lanes, Off-line travel time, Performance monitoring. Travel time is not directly calculated live from VDS data due to accuracy and reliability of MVDS. The intermittent behavior of the MVDS has the potential to make live travel time posting unreliable. MVDS data are used off-line to produce the calculations.

Bluetooth detectors are being deployed at selected segments for travel time calculations. However, this detection technology constitute a sampling technique for Origin-Destination studies using vehicle re-identification.

3.2.7.2 Causes of VDS Failures

MVDS configuration is said to drift over time from the initial settings with no assignable cause. Other causes of failure include calibration errors, bracket loosing position in older MVDS models and lightning.

It was noticed during off-peak periods (at night or early morning) speed readings with no associated volume or negative values of speed. In some cases lower speeds than expected were registered under low density conditions.

3.2.7.3 Maintenance Practices

Installation tests are performed in the field with remote assistance of ITS personnel from the control room. Tests performed on controlled access segments using the toll gantry as the ground truth. The controlled segment do not have entry exit ramps over an extended length. MVDS on the controlled segment are compared with entry point data and some discrepancies were observed. Test follow a similar document than the one used in District 6.

3.2.7.4 Additional Findings and Lessons Learned

MVDS were used in a pilot project for wrong way detection but the system was not accurate enough to support the application. FTE is currently testing infrared video technology as an alternative to MVDS for wrong way detection applications.

Detector density is currently one MVDS per 1/2 mile. There are plans to reduce MVDS density in rural zones to one detector per mile. For express lanes applications detector intervals of 1/4 or 1/3 of mile are used

Control segments for express lanes may vary, the minimum segment length is three miles as per the Express Lane Handbook. Time aggregation of 15 minutes is generally used for express lanes

3.2.7.5 Cause and Effect Diagram for FTE

Figure 16 summarizes the experience of FTE with MVDS installation and maintenance. It can be observed that as with all the field equipment, exposure to power surges result in maintenance calls. It was found that communication equipment may fail more often than MVDS for multiple reasons with power surge being the most cited. Calibration errors also accounted as one of the causes of MVDS accuracy fluctuations. Calibration of MVDS involve several aspects including tools (e.g., laser gun), training of personnel, test methods, installation methods among the main factors. Misaligned head also was observed which was caused by the mounting bracket.

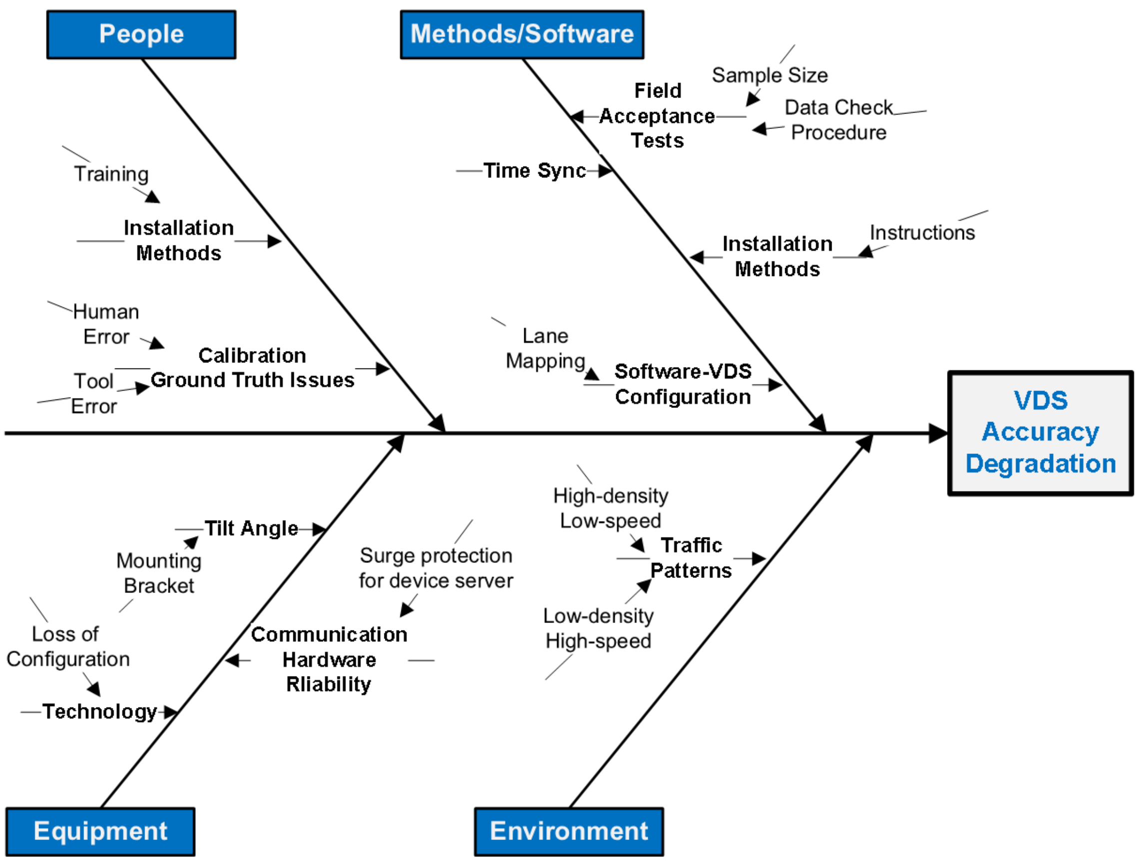


Figure 16: Cause and Effect Diagram for FTE

3.3 Analysis of VDS Experience

Based on the information gathered from several FDOT Districts, a synthesis of VDS experiences and practices was performed. A fault tree diagram was used to characterize the cause of VDS failure statewide. Also, analysis contexts were created with the information provided by the Districts about their experience with installation and performance of VDS for TMC applications. It was also necessary to define several levels of raw data. The concept of raw data depends on the consuming application. These definitions were used to analyze current practice on the calibration of VDS, establish failure modes, and to provide recommendations.

3.3.1 MVDS Context and System Architecture

The main stakeholders of the system includes VDS suppliers, TERL, Field Installer, TMC operator, and the VDS data consumers. Data consumer stakeholders can be other agencies (e.g., planning) or the public through a DMS. In the broader context, the TERL interacts with MVDS vendors and the TMCs through the Specification 660 and the procedures for inclusion in the APL. The TMC has many MVDS subsystems and interacts with the installer and data consumers. The environment play a role providing operating conditions for the TMC and the MVDS subsystems. This is captured through the block definition diagram in Figure 17. The block definition diagram is a formal way of capturing the structure a system using the Systems Modeling Language (SysML).

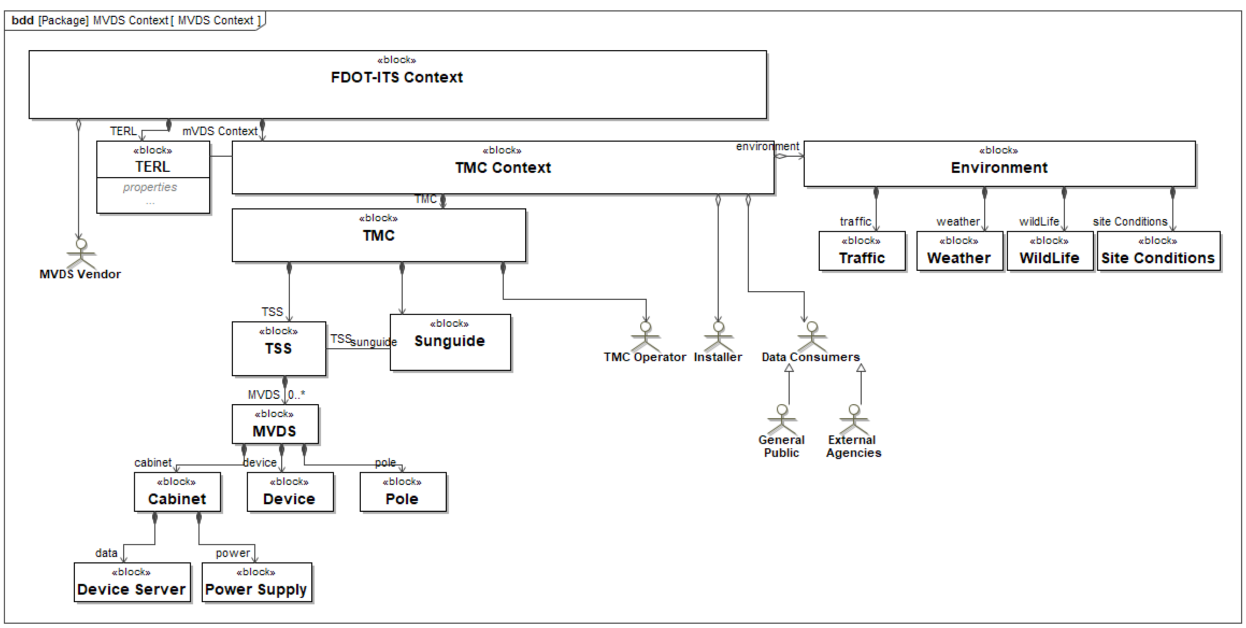


Figure 17: SysML Block Definition Diagram of the MVDS Context

The key use cases for the systems under consideration are presented in Figure 18. The TERL establishes the requirement and the design approval tests for VDS. VDS suppliers follow the procedures to obtain approval. On the TMC context, the Field Installer installs the approved VDS and tests it according to requirements in specification 660. On the TMC side, a designated operator verifies that the VDS operates as intended. In case of performance fluctuations, the

TMC operator may troubleshoot the MVDS remotely. The TMC operator may have other capabilities of interaction with the TMC depending on software-hardware capabilities. Field tests are conducted on the raw data from the detector, while verification at the TMC is performed on data that has been post processed by SunGuide. The pass/fail criteria for each of these tests are derived from specification 660. However, there is flexibility for each District on how the installation and verification tests are conducted. These tests would not only involve detector data itself but also include hardware-software integration as presented in the next section

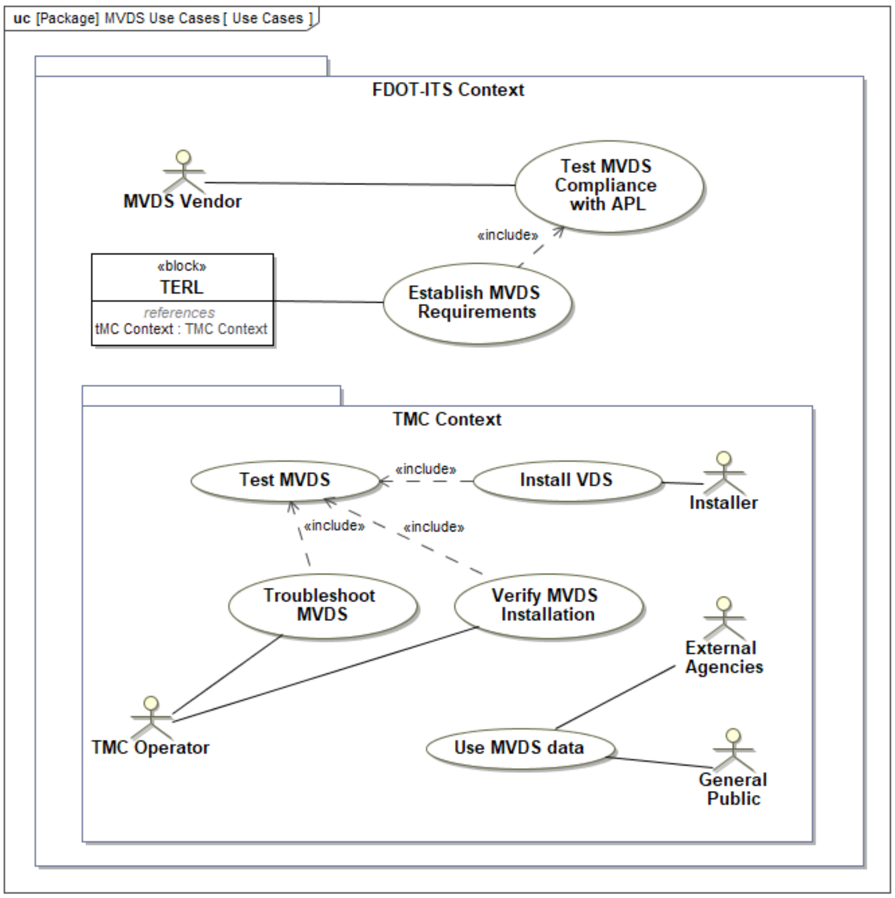


Figure 18: VDS Use Case Diagram

3.3.2 VDS Raw Data Definition

Traffic monitoring is a core function for ITS systems and as such it is contained in a well-defined system architecture. This architecture is executed through the SunGuide software. Traffic Sensor Subsystem (TSS) is the subsystem allocated to handle detector configuration and data management. Figure 19 presents the levels of raw data in the SunGuide architecture.

Using a formal classification scheme, as shown in Figure 19, the true raw data are a level 1 data taken as it is registered by the detector, residing in the detector's memory bank and using its time reference. However, the system monitoring function requires a unified timeframe and the detector time stamp is omitted in an intermediate process. Also, the lane numbers are designated differently in the detector and in SunGuide. For that reason, detector lanes are mapped onto the corresponding system lanes according to the SunGuide lane numbering convention. This data corresponds to level 2 in Figure 19. Once the data are physically at the TMC in the system database, the data are stored in this level 2 format but it is also aggregated into a more usable interval generally over a minute depending on the District policy. This last stage of VDS data are considered raw for some applications and is further aggregated by distance and/or time.

When a TMC operator verifies a VDS installation using received data, there will be some intermediate manipulation in what is considered raw data. This can lead to some discrepancies when comparing with VDS field data. These discrepancies are attributed to the interaction of hardware and software elements.

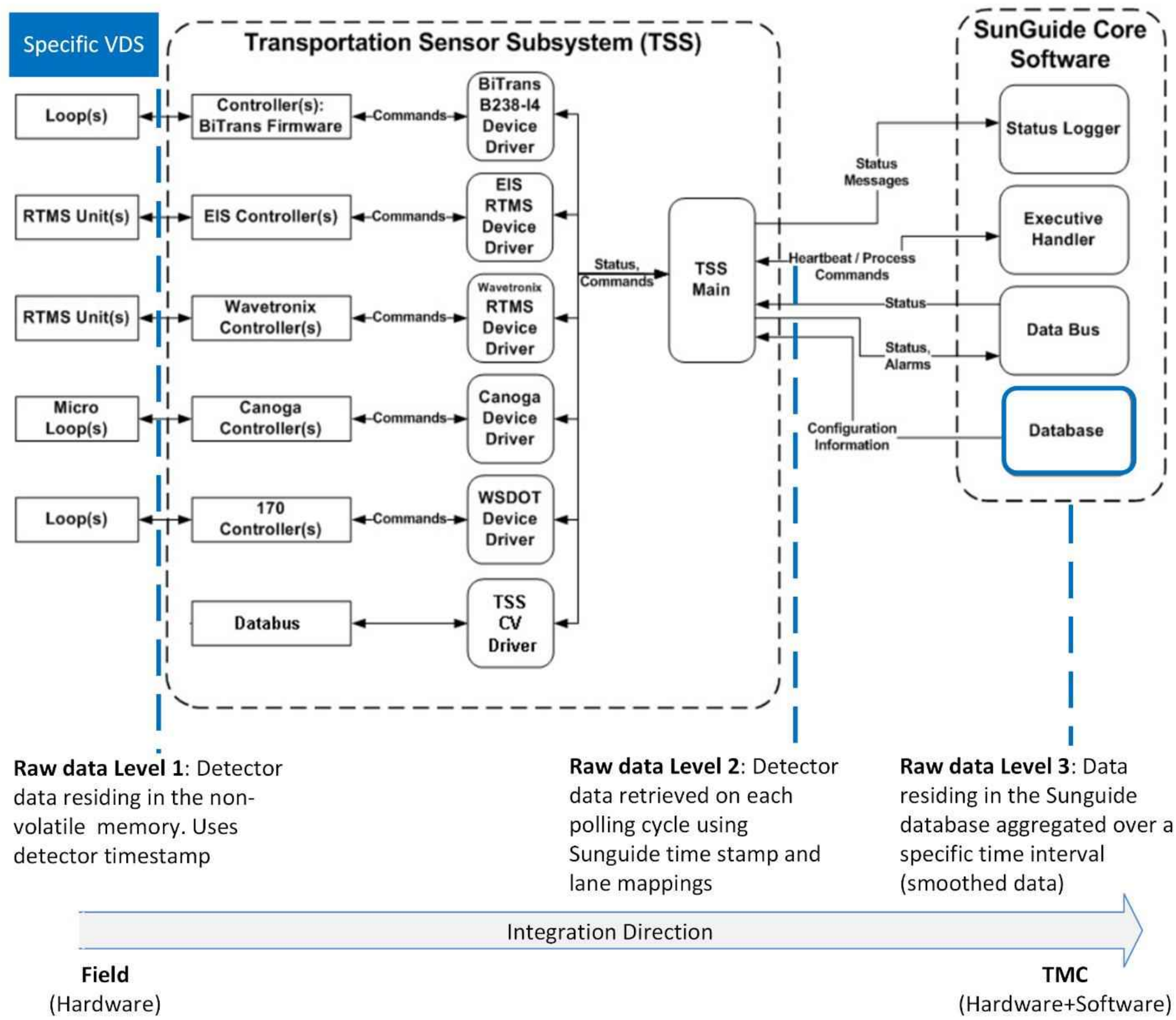


Figure 19: Levels of VDS Raw Data in the SunGuide Architecture

3.3.3 VDS Data Retrieval Mechanism

VDS devices are connected to the TMC software (Sunguide). Serial or Ethernet communication connectivity is required (Standard specification 660-2.1.2.3.1). Also, application programming interfaces (APIs) are required to integrate the VDS to the TMC. Using APIs and the functionalities provided by the VDS vendor, the TMC can remotely manage and operate the field units. SunGuide retrieves sensor data using a polling mechanism. The system sends a request for data to the VDS at defined time steps or polling cycles. The VDS responds to this polling request by sending data from the most recently completed interval. The duration of polling cycles varies by District but typical values are 20 and 60 seconds.

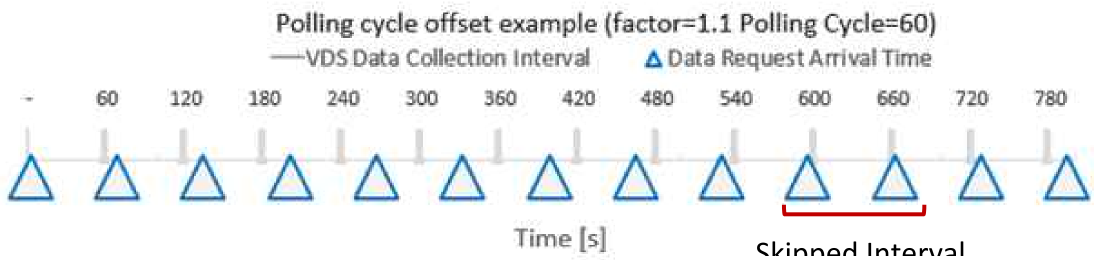
The detector stores the data element from each completed interval in its internal memory. The internal memory is generally an ordered list in the form of a stack. The stack has a Last-In-First-Out (LIFO) queuing policy. This means that the most recent data element is located at the first position in the list and it is also the first to be retrieved. It also follows that once the capacity of the memory is full, the last element (oldest data) is eliminated and the most recent is added to the beginning of the list.

Once a time interval is completed, the associated data element is placed at the top of that stack and is considered as the most recent data element. As part of the data retrieval process, the TSS main subsystem sends a request for the most recent interval of data. The interval located at the first position of the stack of all completed intervals is then sent to the requesting object. This process is repeated for every polling cycle. The retrieved data are time stamped using SunGuide which takes place after the polling cycle is completed. Therefore, there is a systematic delay of one polling cycle between the actual time of the detector count in the field and the timestamp of the retrieved data. Polling cycle offset can cause systematic effects such as double counting or interval skipping, as explained in the following section.

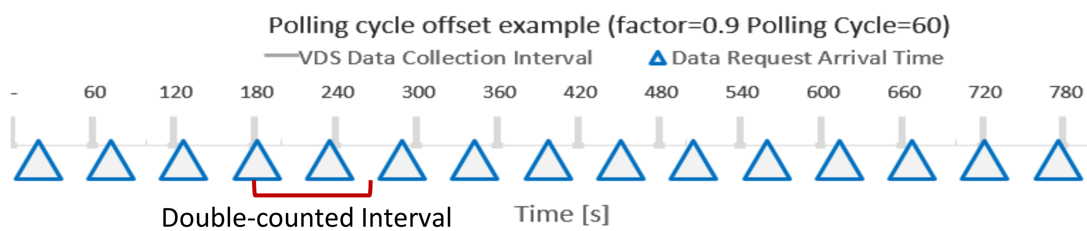
3.3.3.1 Effect of Polling Cycle Synchronization

In the scenario where all detectors and system clocks are synchronized, data can be polled either with a shorter or longer period than the interval's fixed period. This means that polling is either more frequent or less frequent than the interval period on the detector's ends. This difference in polling frequency can occur for a number of reasons, such as server or network communication delay, configuration changes or software issues. This can also occur on the VDS' end due to software configuration changes.

Figure 20 illustrates an example of the effect of the difference in polling cycle intervals between the detector and the data retrieval system. The polling cycle offset factor multiplies the intended system polling cycle to reflect polling cycle offset on the data retrieval system. For example, a polling cycle offset factor of 1.1 means that the polling cycle duration for the data retrieval system is 10 percent greater than VDS data collection interval. In this case, the retrieval system has a less frequent polling cycle (slower polling rate) and some VDS intervals are skipped (see Figure 20 a.). Interval skipping happens because the detector interval time has already passed when the detector receives the request for data, and a new interval has already been placed on top of the stack as the most recent. Interval skipping causes the system to retrieve the next interval of data to be processed and timestamped. Figure 20 b. presents an example of double counting an interval. This effect occurs when the polling cycle duration of the retrieval system is shorter than the data collection interval of the VDS.



a. Interval skipping



b. Interval overcounting

Figure 20: Examples of Polling Cycle Time Offset

Figure 21 shows the effect of different polling cycle offset factors. Interval skipping occurs when the data retrieval system runs at a faster pace than the time interval at the VDS. Interval skipping and overcounting are proportional to the polling cycle offset.

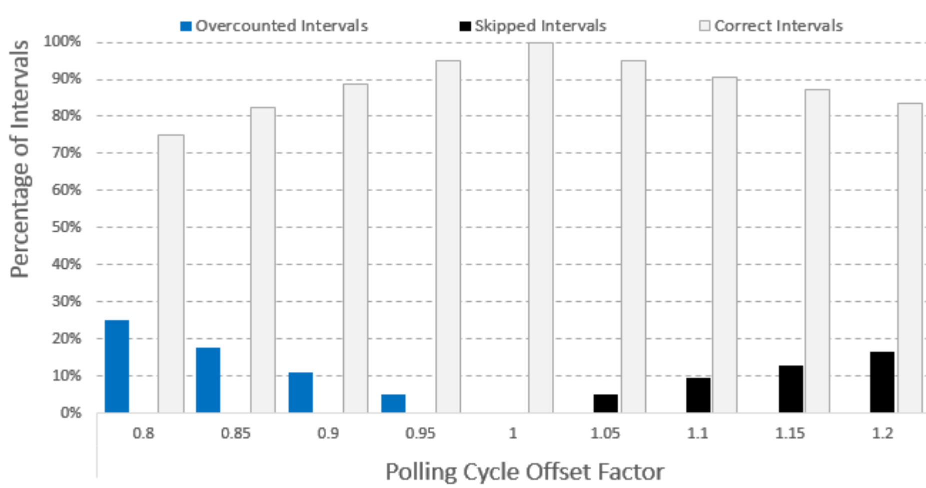


Figure 21: Effect of Polling Cycle Time on VDS Data

A polling cycle five percent less than the intended value will tend to skip the same percentage of intervals. The same applies to the overcounting side of the graph. Since the estimate of interval skipping and overcounting is a deterministic calculation, results may vary randomly in reality depending on the traffic variable of interest and the number of vehicles in the skipped/overcounted interval. For volume, polling offset will have noticeable results because volume is accumulated over time. For speed, the effect of polling time offset is averaged overtime therefore double counting or skipping will not severely affect the measurement.

3.3.4 Fault Tree Analysis

Fault Tree Analysis is a well-known method used to gain a thorough understanding of the basic causes leading to a failure event in a device or a system. A fault tree (FTA diagram) is typically used to explicitly show the different relationships that are necessary to result in a failure event. The fault tree (see Figure 23) was an effort to identify and summarize the possible root cause(s) of the inaccuracy in the VDS data received by the TMC applications. The FTA was based on the internal block diagram of the TSS subsystem in Figure 22.

The fault tree provides a tangible record of the systematic analysis of the logic and basic causes affecting the VDS accuracy, consistency, and reliability. The fault tree consists of basic events (circles), intermediate or top level events (rectangles), and logic gates (OR gate symbol). The basic events are inputs to the OR gates. The outputs of the OR gates (intermediate and top level events) are true if any of the inputs (basic events) occurs. This fault tree includes events observed by FDOT Districts as to what causes might have possibly resulted in the failure of the VDS or in erroneous data received by the SunGuide applications. At the top of the FTA is the undesirable event (see Figure 22), i.e., inaccurate VDS data for the TMC applications. This undesired event can occur based on three events, either, the VDS is physically damaged, or the VDS transmit data incorrectly, or there is a network communication problem. There are several factors that can lead to the VDS to transmit incorrect data. It could be VDS parameters entered incorrectly, polling cycle problems, or incorrect lane mappings to TSS links. In a similar manner, the fault tree can be traversed from all the root nodes to determine the different failure events for a VDS.

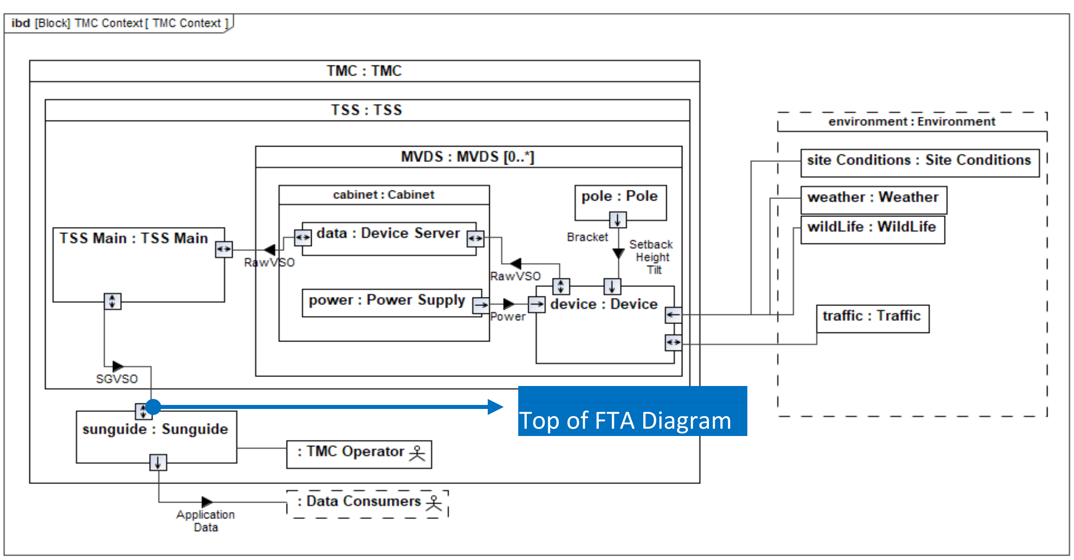


Figure 22: SysML Internal Block Diagram

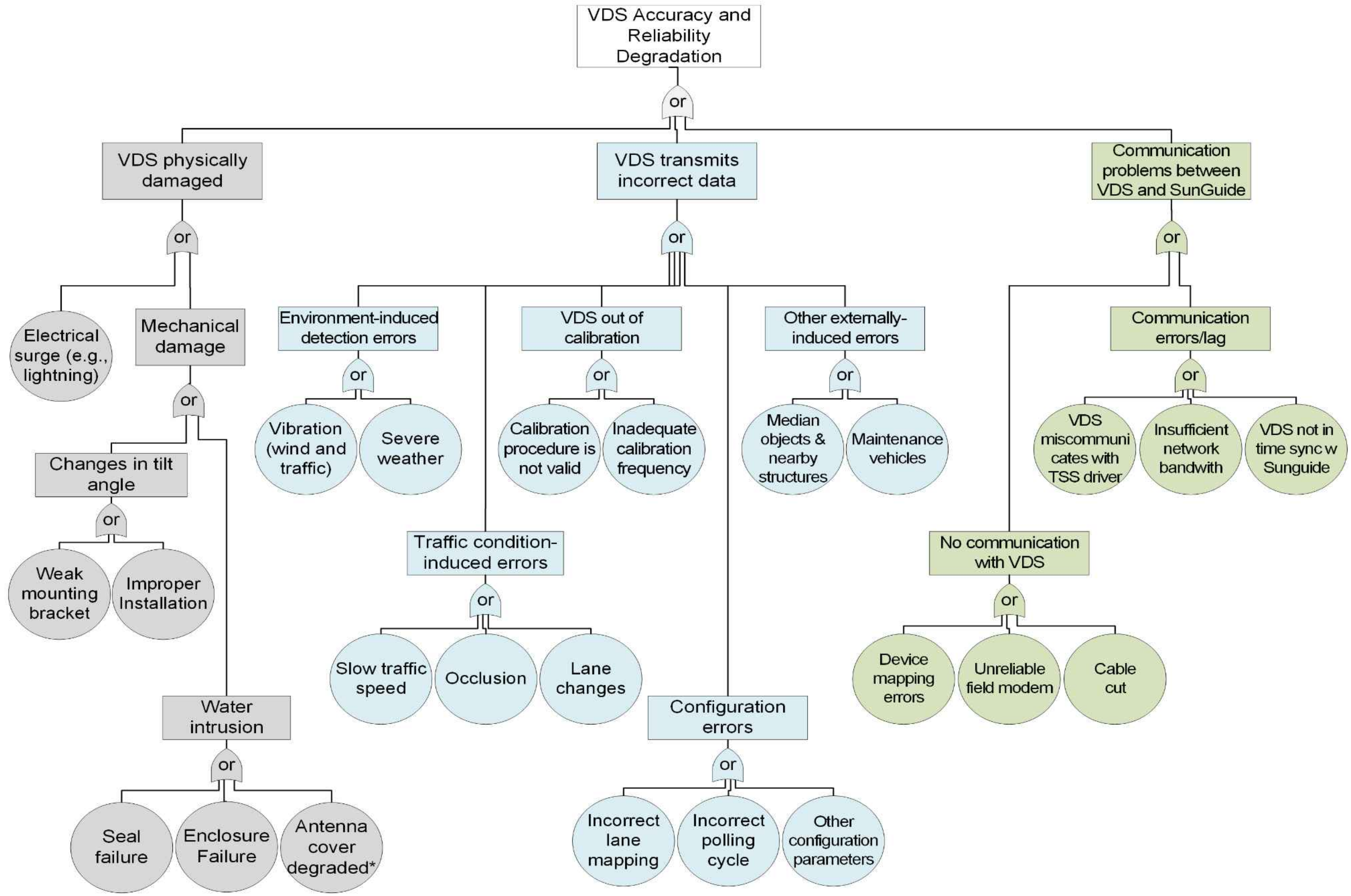


Figure 23: VDS Fault Tree Summary

3.3.5 Requirements Testing for VDS

FDOT Specifications 660 contains a set of comprehensive VDS requirements of various types including functional, performance, physical construction, electrical, mechanical, installation requirements, etc. These specifications also define test procedures for verifying functional and performance requirements for VDS devices as presented in Figure 24. Some of the tests are performed supervised by TERL as part of the product certification process for Florida APL such as the VDS accuracy performance test. Other tests are performed by FDOT districts as part of the device installation and/or field calibration procedures such as the Field Acceptance Test (FAT). Each test attempts to verify a predetermined set of requirements. The allocation of requirements to test cases for verification purpose is carried out through a Requirements Verification and Traceability Matrix (RVTM). An example of the RVTM is presented in Figure 25. The arcs joining requirements and test cases are represented in tabular form in the RVTM. These arcs can be read in two ways. From the requirements to the test cases the RVTM are read as a "verified by" relationship, and from the test cases to the requirements is read as "verifies". From the test viewpoint, the test verifies that the requirement is met by the VDS under study.

Using a structure such as an RVTMS allows for both qualitative and quantitative requirements analyses. It can help in documentation review, testing procedures review, and coverage analysis. With a coverage analysis, it is possible to determine if a VDS requirement has not been assigned to a test procedure. In those cases, the requirements are reviewed and modified, assigned or retired as per the reviewer(s) criteria. The creation of an RVTM and an "as is" analysis of the current VDS requirements in specification 660 is presented in the next section.

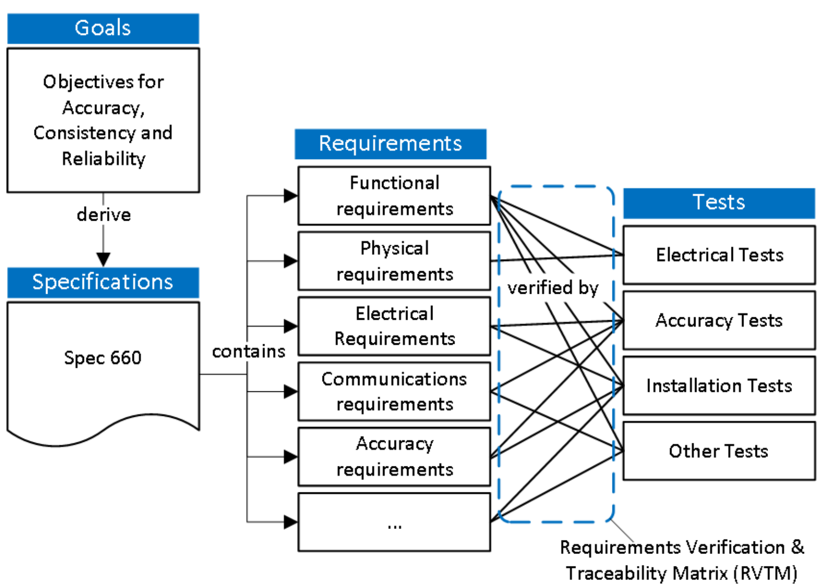


Figure 24: Requirements Verification and Traceability Matrix Concept

3.3.6 Requirement Verification and Traceability Matrix (RVTM)

The RTVM included in the provided spreadsheet is the result of parsing the 660 specifications into its constituent requirements that can easily be grouped into common types, e.g., functional and physical, and can be allocated to various test cases/procedures and organizations where these requirements are verified. These tests can be applied to verify compliance at specific stages of the lifecycle of a VDS (e.g., certification, installation, calibration). The RTVM is described in the Florida's Statewide Systems Engineering Management Plan (*39*) and implemented with the 660 matrix . This is the method typically employed to keep track of where and how each requirement is being tested. The RTVM parameters can be tailored to accommodate the requirement tracking need of different projects. Figure 25 below shows a small sample of the RVTM for VDS.

REQUIREMENTS VERIFICATION AND TRACEABILITY MATRIX					
Project Name:	<optional>				
Manufacturer:	<required>				
Item model:	<required>				
		Requirement Information			
ID	Section	Type	Related to	Technology	Requirement Text
132	660-2.1.2.3.2	Functional	Wireless Communication	MVDS	Ensure wireless communications are secure.
133	660-2.1.2.3.2	Physical	Wireless Communication	MVDS	Ensure wireless devices are Federal communications Commission (FCC) certified.

Figure 25: Sample Requirements Verification and Traceability Matrix

Specification 660 was parsed into 257 requirements. Each of these requirements was classified based on requirement type as functional, physical, electrical, installation, environmental, performance, testing, payment, and warranty. To each requirement was also assigned a verification method and test allocation. The test allocation designates the entity that is more likely to verify the requirement. The columns of the RVTM are defined as follows:

- **ID**: This column contains a unique ID number used to identify the traceability item in the RVTM.
- **Section:** This column contains the ID of any associated items in documents used for requirements tracking such as sections in the FDOT Specifications 660.
- **Requirement Type:** This column describes the requirement type (Functional, Performance Physical, Electrical, Mechanical, Test, Installation, etc.).
- **VDS Type**: This column specifies to which technology each one of the requirements are applicable. Possible selection of technologies are AVDS, MTDS, MVDS, and VVDS. Requirements that apply to all technologies are defined under the type “All”.
- **Requirement Text:** This column contains a description of the requirement.

- **Test Information**: This column contains a description of how the requirement is verified (Inspection, Analysis, Demonstration, or Test). The verification methods are defined as follows:
  - Inspection: Measured or observed characteristics of the VDS is compared to a standard by a person, who is possibly aided by tools or machines.
  - Analysis: The VDS design is examined by a person, who is possibly aided by a computer model or simulation, for compliance with requirements by understanding its components and design relations.
  - Demonstration: The VDS is manipulated in accordance with instructions and the outcome is compared with the planned results.
  - Test: The VDS is subjected to a controlled series of stimuli, and the VDS response is monitored and compared with a standard, expected, predicted results.
- **Additional Comments**: This column contains additional comments as needed.

Using the RVTM facilitates requirements allocation, testing, and coverage analyses. Figure 26 presents an analysis of the requirements in specification 660 by type and test allocation. It is observed that most of the functional requirements are verified at the acceptance stage, helping to reduce the testing needs for field acceptance. As the installation and integration stages progress, it is expected that the majority of testing on the TMC side is focused on performance verification. For instance, communicating with the VDS implies functional device, communications, electrical etc. The TMC requirements are important to verify installation methods as noted in the cause-effect analysis. It is recommended that specific TMC-side tests and verification procedures are formalized. TMC-side tests may also include application-specific tests for travel time posting or managed lanes.

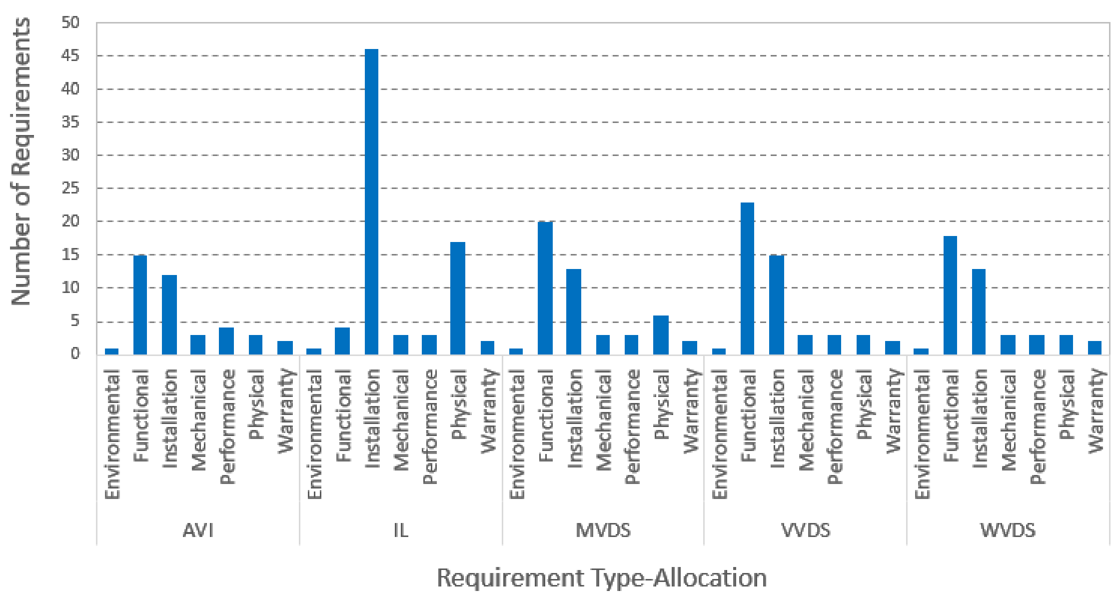


Figure 26: Requirement Type Allocation

3.3.7 VDS Installation Testing Practice

Based on the reported tests and maintenance practices for the interviewed Districts, a summary of inspection tests was developed (see Table 11). The objective of this comparison is to find the common inspection elements in order to provide a unified comprehensive test with the best practices among the districts.

Table 11: Summary of Functional Checks before Performance Tests

Structural Inspection
Visual/Electrical safety inspection
Make sure that MVDS is the latest version/generation. Replace if necessary
Make sure that the two co-located MVDS are on two separated communication networks with separate fiber optics and layer 2 switches
Verify quality and tightness of ground and surge protection connections
Verify device physical construction, connections to power and cabinet, proper labeling of components and cables
Verify voltage for all power supplies and circuits
MVDS Positioning
Angle adjustment
Measure and document detection area, setback, and mounting height
Establish communications between a laptop computer and the MVDS
Message period verification: set up communications between laptop and MVDS and check that the message period is set as 20 seconds
Verify that the MVDS is storing data
Data comparison between internal storage of the detector and data received by SunGuide
Verify that the MVDS is able to collect and process volume, speed, and occupancy lane by lane

Table 11: Summary of Functional Checks before Performance Tests (continued)

Lane configuration check
Detailed lane configuration (MVDS zone, SunGuide lane and zone information) should be available to the technicians
Confirm that each managed lane and general purpose lane detected is an individual zone
Verify that lane setup was done correctly and all intended lanes of detection are displayed and storing volume and speed data
Self-test and start-up parameters check
Contact between technicians in the field and TMC operator

The summary of performance tests for volume is presented in Table 12 below. It is observed that time intervals and sample size vary. Districts 6 and 7 tests require 200 vehicles per lane while D4 tests suggest 100 vehicles for all lanes combined. The number of trials was a special consideration for the test in District 6 and will be part of the verification experiments. District 6 document has been widely adopted by other jurisdictions such as Districts 2, 5, 7, and FTE [5].

Table 12: Summary of Performance Tests for Volume

	Ground Truth	Sample Size		Acceptance Criteria	
		Time	Events	Per Lane	Overall
D1	Tally Counters	10 minutes	N/A	Error per lane was calculated but it wasn't used as an acceptance criteria	The total count of all lanes combined from the MVDS shall result in less than ±5% error when compared to the counts from the Tally Counter
D4	Tally Counters	5 minutes	100 vehicles (lanes combined)	Error per lane was calculated but it wasn't used as an acceptance criteria	The total count of all lanes combined from the MVDS shall result in less than ±5% error when compared to the counts from the Tally Counter

Table 12: Summary of Performance Tests for Volume (continued)

	Ground Truth	Sample Size		Acceptance Criteria	
		Time	**Events**	**Per Lane**	**Overall**
D2 D5 D6 D7 FTE	Tally Counters	15 minutes	200 vehicle speeds per lane	The count per lane from the MVDS shall result in less than ±5% error when compared to the counts from the Tally Counter	If the same lane fails for a second time, after adjusting the sensitivity, the calibration is stopped and the unit replaced

The characteristics of the performance tests for speed are summarized in Table 13. Districts 6 and 7 tests require larger sample size collected in the field. This is beneficial for the test itself but it could make calibration more time consuming.

Table 13: Summary of Performance Tests for Speed

	Ground Truth	Sample Size		Acceptance Criteria	
		Time	**Events**	**Per Lane**	**Overall**
D1	Radar Speed Gun	5 minutes	N/A	The average speed for the selected lane (only one lane tested per detector) from the MVDS shall result in less than ±10% error when compared to the average speed from the Radar Speed Gun readings	N/A

Table 13: Summary of Performance Tests for Speed (continued)

	Ground Truth	Sample Size		Acceptance Criteria	
		Time	Events	Per Lane	Overall
D4	Radar Speed Gun	15 minutes	8 vehicles speeds per minute	None	The total average speed from MVDS (all vehicles during the 15 minutes period or at least 100 vehicles per lane) shall result in less than ±10% error when compared to the total average from the Radar Speed Gun readings
D2 D5 D6 D7 FTE	Radar Speed Gun	15 minutes	100 vehicle speeds per lane	The average speed per lane from the MVDS shall result in less than ±10% error when compared to the average speed from the Radar Speed Gun readings	If the same lane fails for the second time, after speed coefficient adjust, the calibration is stopped and the unit replaced

4 Data Quality Requirements for TMC Applications

This section presents a data simulation approach aimed at estimating the effect of VDS data accuracy fluctuations in TMC applications. First, a VDS data lifecycle characterization is provided. In addition, a selected set of TMC applications was studied in terms of data inputs and decision-making process. Simulated VDS data were used to induce accuracy fluctuations and determine the levels of acceptable performance for the selected VDS applications. The final section provides recommendations of requirements for VDS deployments.

4.1 VDS Data Lifecycle

VDS data have a lifecycle as depicted in Figure 27. Data collection is planned, and then, the corresponding VDS infrastructure is deployed. Data are collected by the VDS, loaded by the traffic sensor subsystem, and stored in a database. TMC applications may request data at a specific frequency and with different levels of aggregation. The aggregated data are used by the consuming TMC application to make a decision, e.g., calculating toll rates or posting travel times. The VDS data are archived for later usage. VDS data may be audited and, if needed, new plans are generated to collect data. Additional applications such as traffic studies can make use of archived data. Any given segment of VDS data are active while are valid for the current traffic conditions, leading to a decision by the consuming TMC application. The life cycle of the VDS data may vary with respect to the application, generally ranging from under one minute to one hour, with 15 minutes being the most common time aggregation level.

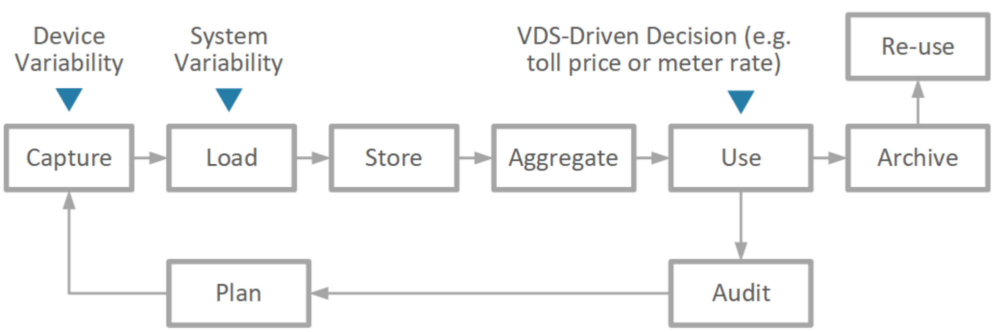


Figure 27: VDS Data Lifecycle

4.2 VDS Variability and Bias

This section establishes the assumptions of sources of VDS data variability at the point of consumption for TMC applications. There are several sources of variability for a given VDS installation. There is variability due to the prevailing conditions at the site (e.g., traffic patterns, environment, etc.). Prevailing conditions variability is considered as a non-controllable external factor. Only some interaction effects can be explored with readily available data (e.g., accuracy by season). Other sources of variability are device variability and system-software variability. Device variability is due to the technology, materials, assembly process, and algorithms that compose the VDS product. This type of variability is a characteristic of the device itself. The system-software variability refers to the system (i.e., SunGuide) that takes data from the VDS and processed it until consumed by the TMC application. In both cases (device and software-system), variability can be decomposed in natural variability and explained variability. Explained variability for the device can occur by several causes including incorrect setup, aging equipment, water intrusion, incorrect tilt angle etc. Natural variability on the other hand is a characteristic of the product itself and cannot be modified with setup or calibration.

System-software variability, refers to errors induced by the software and hardware that carries the data from the VDS to the central database. Explained variability for the system may include configuration, synchronization, network capacity etc. Natural variation corresponds to emergent properties for hardware-software interaction when all the software components are operational. Besides configuration aspects, system-software variability is difficult to track outside a software testing environment.

Natural variability is random in magnitude and direction. Its magnitude is in general limited to some practical value. This is equivalent to the ± error term usually found in the specification of a VDS. The implication of natural variability is that at any given measurement, the device can overestimate (+) or under estimate (-) the variable being measured but on average, it should be on target. Any bias in the measurement will make the estimation consistently on overestimation (or underestimation). Bias is considered a systematic error and can be corrected by calibrating the equipment improve accuracy. The ± error is a claim of the manufacturer and it subjected of verification and monitoring.

4.3 VDS Data Characterization for TMC Applications

Traffic conditions can be described by several measures of effectiveness. Most of these measures are derived from fundamental traffic variables. These fundamental traffic variables are speed, volume, and density. Furthermore, by knowing any two of these variables the third one can be estimated. Likewise, traffic monitoring system rely heavily on speed and volume measurements as a way to derive other system performance variables to be consumed by TMC applications.

Once a VDS is installed, it is expected that some deviations in accuracy may occur. These deviations could be from natural causes or due to attributable causes. Any sample of VDS on any given segment may present a random deviation from the target accuracy. The way in which these deviations affect the performance of the supported TMC application is relevant for system upkeep decisions and technology evaluation for future deployments. These fluctuations may change the decisions executed by the consuming TMC applications, which may affect roadway users. Determining the robustness of such decisions with respect to accuracy fluctuations is the main aspect to determine data quality requirements. Assuming that VDS's in a given segment are operational and that are operating only under natural variation, the effect on TMC applications mainly depends on data aggregation level and detector density.

VDS allow transportation agencies remote monitoring of roadway control section for TMC applications as presented in Figure 28. VDS provide partial view of the traffic conditions on a roadway control section. The control section is divided by segments and a detector is placed within the segment. Each detector collects data on the lanes within the segment. Segments are also referred to as zones and the aggregation of detector data for may be referred to as station. The detectors collect data on small time intervals named polling cycles. VDS data are aggregated through many polling cycles to conform a decision making cycle. At that time an action may be taken based on the application. The data resolution for the TMC is the polling cycles (T) and detector density (S). For each VDS data unit volume (sum), speed (average) and occupancy (average) are collected. The data are aggregated and used depending on the application. For example, assuming a polling cycle of one minute, travel time uses aggregation over all segments in the control section for 15 cycles while a queue detection application may use one segment for 2-5 cycles.

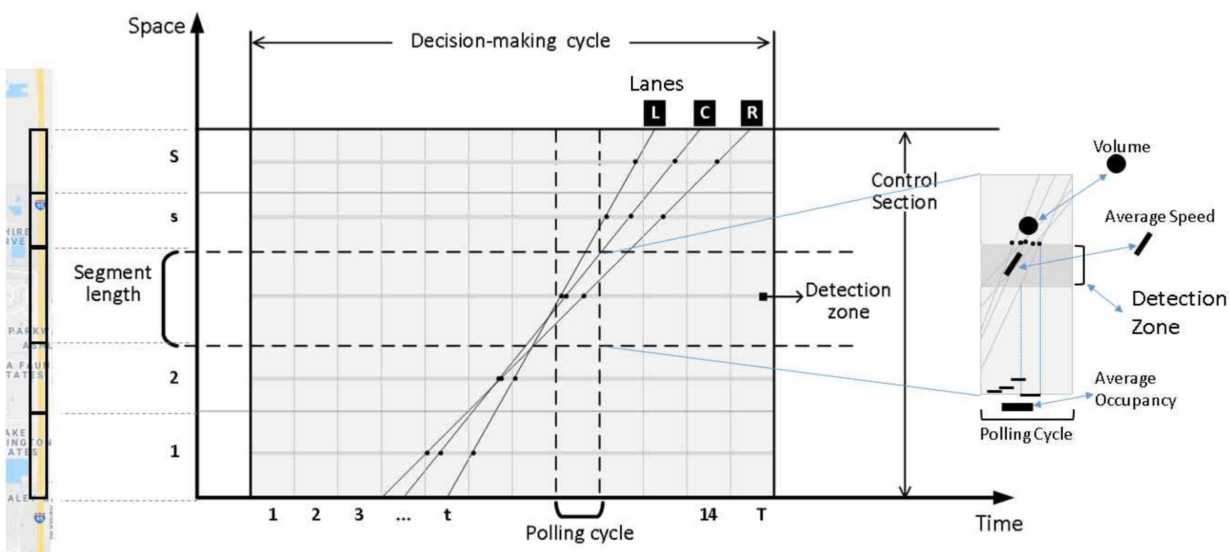


Figure 28: Control Segment and VDS Data Collection

Traffic monitoring systems generate VDS data consumed by other systems for different applications. These applications may have diverse requirements with respect to accuracy, aggregation level, and life cycle of the input data. Figure 29 presents approximate relationship between aggregation levels and TMC applications for long-range planning, data are aggregated over time and roadway segments. Examples of highly aggregated data include Average Annual Daily Traffic (AADT) and Vehicle Miles Traveled (VMT). On the other hand, real-time traffic monitoring such as detecting a queue backing up on an interstate or wrong way traffic require site-specific data with little or no aggregation over a shorter life cycle.

First, the detector failure modes are explored. Once the likely failure scenarios are determined, these scenarios are applied to selected TMC applications. Models are iterated to obtain a sensitivity chart for each TMC applications. The sensitivity chart was used to produce a requirement for the selected TMC application.

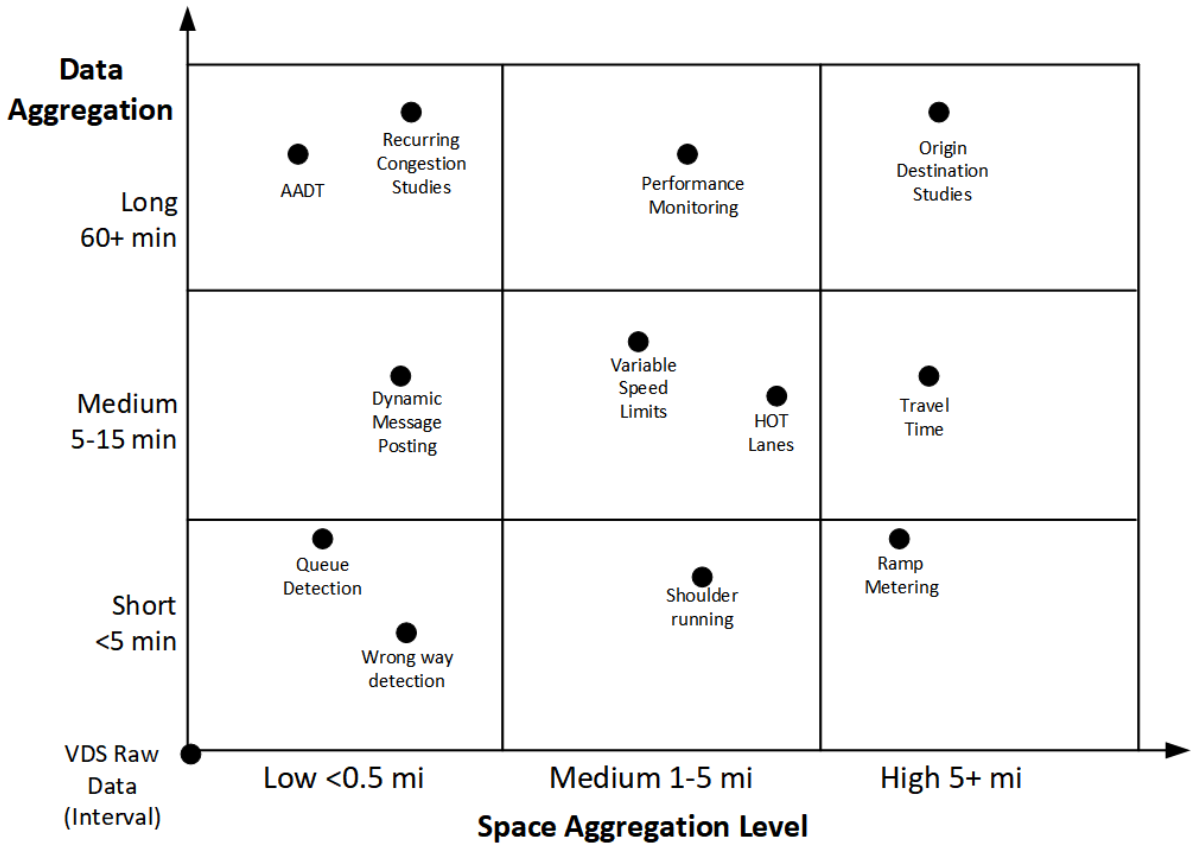


Figure 29: Relationship between VDS Data and Transportation Applications

1.1 VDS Accuracy Fluctuation Modes

In order to gain insights on how fluctuations in VDS raw data affects the performance of TMC applications, it is necessary to evaluate the situations in which accuracy fluctuations occur. This can be done for a set of detectors for which ground truth data are known. Data collected form field observations performed in District 4 and reported calibration data form District 1 were used to determine trends in accuracy fluctuations. This can help to predict the VDS accuracy degradation conditions that can be encountered in the field and predict their effect in TMC applications. Sign for accuracy was preserved to keep track of the direction of fluctuation. Data collected for the study contain speed, volume, and classification. For this analysis volume and speed was used along with data reported data from calibration reports performed by VDS installers.

Table 14: Performance Measures of Effectiveness for Interval Data

Measure	Formula
Volume Accuracy (percentage)	$\frac{V_{vds} - V_{gt}}{V_{gt}}$
Speed Accuracy (percentage)	$\frac{S_{vds}V_{vds} - S_{gt}V_{gt}}{V_{gt}}$
S_{vds}: Speed measured by VDS V_{vds}: Volume measured by VDS S_{gt}: Ground truth speed V_{gt}:Ground truth volume	

The purpose of the analysis was to visually analyze the trends and determine extreme cases and gain some general insight of VDS accuracy. Figure 30 presents a scatter plot of speed error percentage vs volume error percentage. In the plot, the diamond shapes represent detectors in the I-95 corridor (single manufacturer/model) that have been recently installed. The triangles represent a mix of detectors (manufacturers/models) in the I-75 corridor. The lines represent the accuracy requirements for speed and volume as stated in spec 786. The shaded rectangle is the intersection of the accuracy requirements. Each detector corresponds to a volume-speed error pair in the scatter plot. It can be observed from the plot that volume accuracy fluctuations are more frequent than speed fluctuations. This observation can be generalized based on the number of points outside the performance limits for speed (3 points out 56). On the other hand, volume accuracy fluctuations present 14 points out of the volume accuracy requirement zone (out of 56). Given that a particular lane-detector pair is out of the compliance zone, there are 11 points in the overcounting region and nine the undercounting region. Looking at the per-corridor data for volume fluctuation, six points are in the overcounting zone and eight in the undercounting zone for the I-95 corridor. For the I-75 corridor, five points were in the overcounting area and one in the undercounting region.

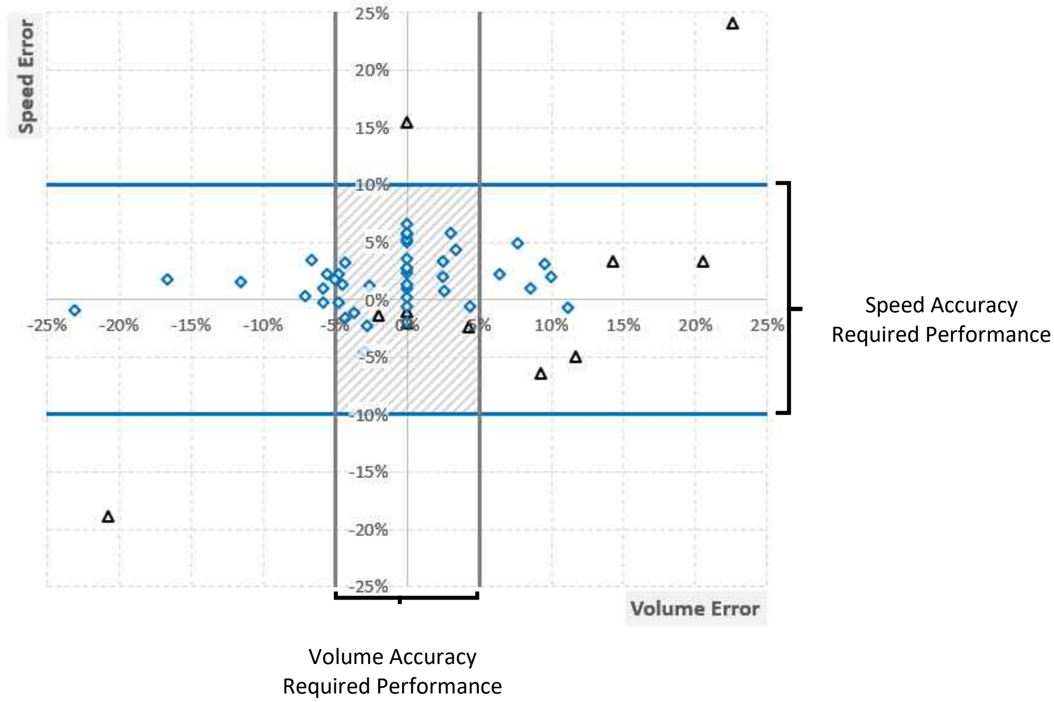


Figure 30: Speed and Volume Accuracy Exploratory Scatter Plot

Modeling detector failures at the lane level will allow emulation of the conditions encountered in the field. To apply the detector behavior in the next analysis step, it is important to determine whether this fluctuation occur independently by lane and by measured traffic variable.

Based on the data in Figure 30, a correlation analysis was performed on the field data. The analysis is presented in Figure 31. The correlation matrix provides a correlation coefficient of 0.2123 between speed and volume. A correlation coefficient value becomes meaningful starting at 0.5 or greater. The obtained value indicates a weak relationship between speed and volume errors. In this case, it can be assumed that speed and volume can fluctuate independently at the lane level. For example, any detector, at any given point in time in a lane, could be overestimating volume while speed estimation may be on target. There is no direct or inverse proportional relationship between speed error and volume error. This type of behavior was observed in the field and it was also reported during interviews with ITS engineers.

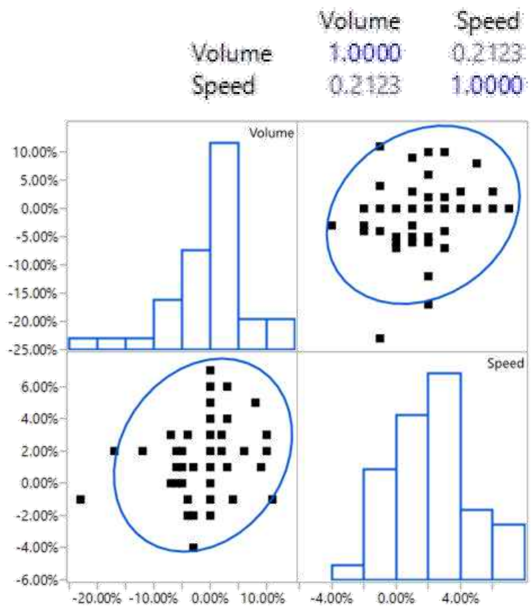
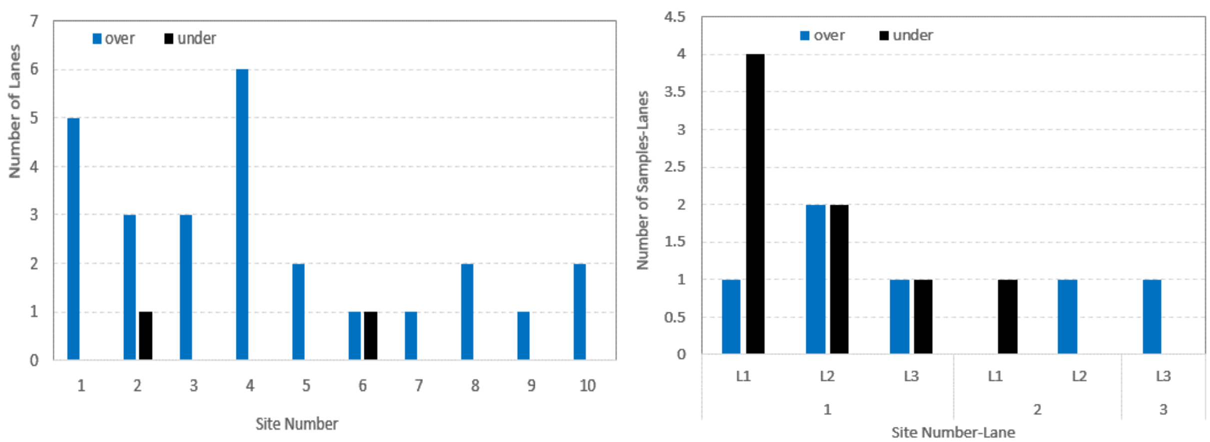


Figure 31: Scatter Plot Analysis with Correlation Matrix

At the station level (detector site), fluctuation modes for VDS accuracy need to be evaluated. The station analysis will focus on volume since this is the more likely failure to occur. The purpose of this analysis is to determine whether all traffic lanes have the same fluctuation trend (e.g., all overestimating or all underestimating).

Two different fluctuation behaviors were extracted from the obtained data and presented in Figure 32. The bar represents the number of lanes over/undercounting per detection station. Sites with both under and overcounting behavior indicate that these events may occur independently. Data in Figure 32 s only include samples that have a lane out of specification for volume.



(a) (b)

Figure 32: Volume Accuracy Fluctuation per Station-Lane

On the one hand (Figure 32.a), a systematic overestimation volume error is observed in the samples for calibration data in District 1. On the other hand (Figure 32.b), collected data indicate that there is no conclusive volume fluctuation trend.

Collected data were used to address the trend in volume fluctuations at the station level. Initially a site-lane box plot chart was constructed (see Figure 33). The lanes are represented by different shapes on the plot. The 0-percent error line was highlighted in the figure for reference. It can be observed that, for the same site in different subsamples, volume accuracy could fluctuate on either side of the 0-error line. These fluctuations are more evident below the ±10 percent error line. For the cases that have more than 10 percent error (single case highlighted in the figure), there was a consistent (large error) trend for a specific lane.

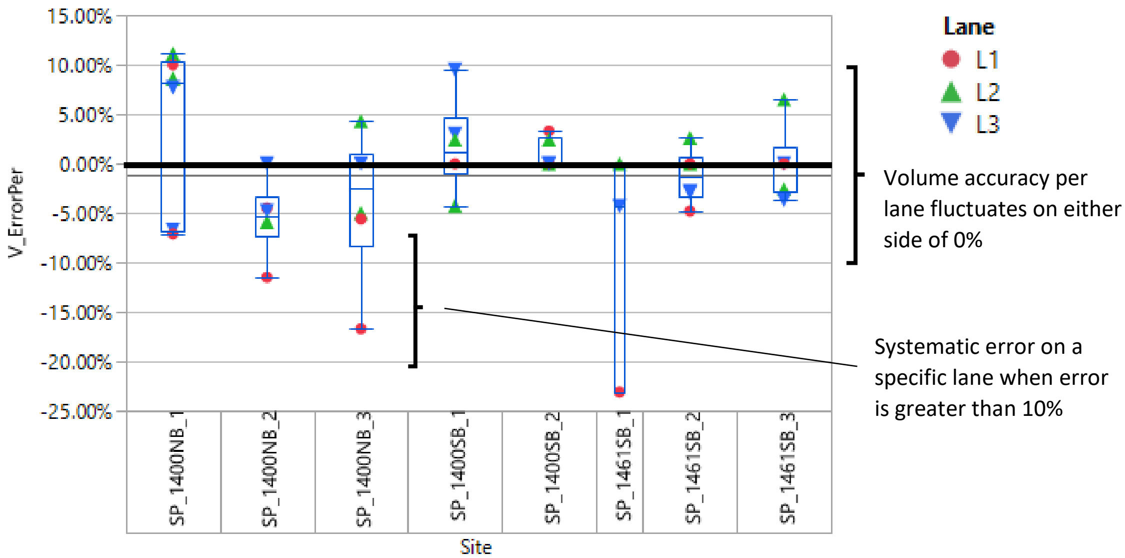


Figure 33: Boxplot by Detector Site and Lane

The observed field behavior and reported calibration data can be used to derive detector accuracy fluctuation scenarios as follows:

- Volume accuracy can fluctuate independently of speed accuracy. Furthermore, volume accuracy tends to be more prone to fluctuate and get out specification than speed accuracy
- Volume accuracy fluctuations can occur randomly due to natural variation within ±5 percent of ground truth scenarios.
- Failure mode 1: Systematic failures on volume accuracy of more than ±10 percent can occur on specific lanes in a single fluctuation direction and independent of other lanes.
- Failure mode 2: All lanes of a detector will fail in the same direction

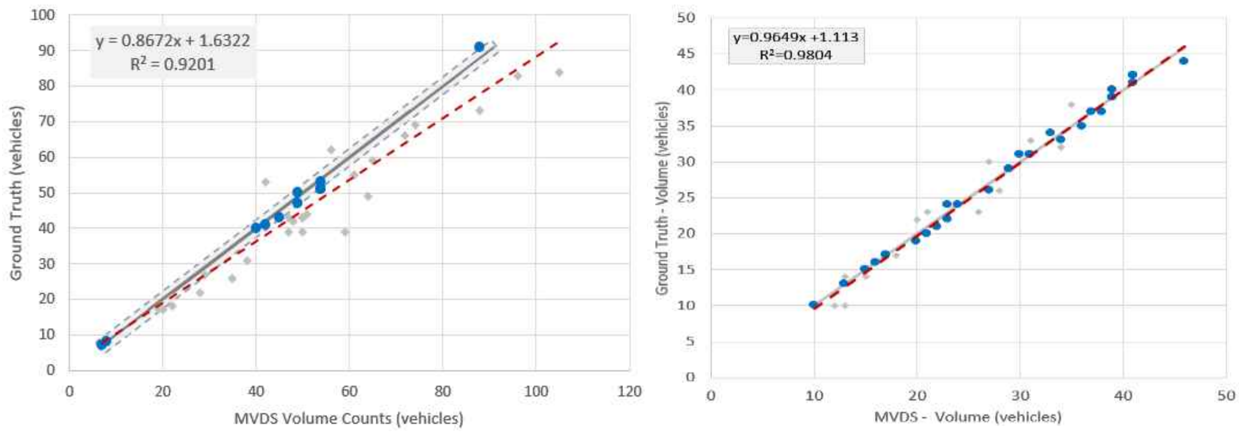
The results of the previous analysis enable the modeling of the most likely failure scenarios encountered in the field. These failure scenarios are used to revise the current requirements in order to determine the minimum levels of accuracy for the specific TMC applications.

1.2 VDS Measures of Effectiveness

VDS measure traffic system status for decision making in TMC applications. In order to determine the required accuracy levels for an application, it is necessary to determine a measure of the system status starting from lanes, station up to segment (system). Then, the system status needs to be mapped onto the decision making process for the TMC application.

1.2.1 System Measures

The analysis starts with an overview of the system based on the availability of ground truth knowledge of the system status. Using the system status data, a plot of ground truth versus VDS counts for microwave detectors on freeways I-75 and I-95 are presented in Figure 34



Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.6321734	2.402284	0.68	0.5015
V_MVDS	0.8672435	0.043814	19.79	<.0001*

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	13255.961	13256.0	391.7981
Error	34	1150.344	33.8	Prob > F
C. Total	35	14406.306		<.0001*

(a) I-75 sample

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.1130124	0.59069	1.88	0.0663
MVDS	0.9649871	0.020774	46.45	<.0001*

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3981.1077	3981.11	2157.735
Error	43	79.3367	1.85	Prob > F
C. Total	44	4060.4444		<.0001*

(b) I-95 sample

Figure 34: Accuracy and Consistency Measures from Field Data

The side to side comparison illustrates an example of the application of the proposed analysis applied at the system level. Each point represents a data pair consisting of MVDS data and ground truth per lane across multiple locations. The continuous line represents the identity equation y=x, which represents the perfect count performance where the ground truth is equal to MVDS counts. Points falling within five percent of this ideal condition, reflecting the requirement in specification 786, are highlighted using circular markers. The linear fit model (regression equation) provides the experimental relationship between the ground truth and MVDS counts at the lane level. Based on the magnitude of the coefficient of determination, it can be observed that there is a strong correlation between the MVDS and the ground truth in the observed cases.

In the case of the detector sample in Figure 34(a) the MVDS can help to explain 90 percent of the behavior of the volume for ground truth while in Figure 34(b) this relationship is 0.98. The intercept of the linear approximation means that it is expected that the ground truth will be off at least by 1.6 vehicles for the I-75 sample and in 1.1 for the I-95 sample. Further statistical analyses of this relationships showed that the intercept is not a significant term in both cases (p-value greater than significance level 0.05).

The remaining term of the linear equation can be interpreted as if the ground truth could be obtained by multiplying the MVDS by 0.86 in the I-75 sample and by 0.96 in the I-95 sample. This means that there is a systematic tendency for the detectors to overcount such that the MVDS data need to be multiplied by a factor less than one to minimize the error with respect to the ground truth. In the case of the I-75 sample, this coefficient is significantly large and means that the true counts are 13.28 percent less than the MVDS counts.

.In the I-95 sample, the excess is 3.51 percent which is within the target specification. This is an average value of the system as a per lane approach. That means that for some lanes, the accuracy may be above or below this value.

The mean analysis is related to the accuracy of the VDS with respect to the ground truth values. This analysis is complemented by examining the amount of variability with respect to the regression line. This is given by the mean square error (MSE). For the I-75 sample, this value is 33.8, taking the square root is 5.8 vehicles as the standard deviation around the estimated value. For the I-95 sample the MSE is 1.85 (1.3 vehicles). This is an indication of the consistency of the detection system. Both quantities make up for a stable traffic monitoring system. Accuracy will ensure that the estimates of the variable are close on average to the true parameters and the variability measures can make the system decision to be stable over time. Changes on any of those will induce undesirable behavior to the system. This analysis was intended to provide an overview of a group of VDS to identify trends and potential behavior in terms of accuracy and consistency estimation

1.3 Application Analysis

The application analysis consists in revising the key decisions taken by TMC applications based on VDS data. The first step was to determine the most likely fluctuation behavior and to obtain a basic understanding of VDS accuracy at any given time. Based on initial fluctuation assumptions, a system status at the lane level can be simulated to reflect detector accuracy fluctuations. These levels are indicated in Figure 35 and include:

- Perfect information
- Fluctuation within current baseline
- Fluctuation within experimental region
- Fluctuation most likely scenario

A system status will be a complete generation of 1, 2, n lane detector status set. This is modeled based on the type of TMC application. Baseline performance includes perfect information. Another measure is the expected performance which includes fluctuation within the current performance requirement from spec 786. Finally a set of performance metrics in terms of deviation from the intended decision are calculated.

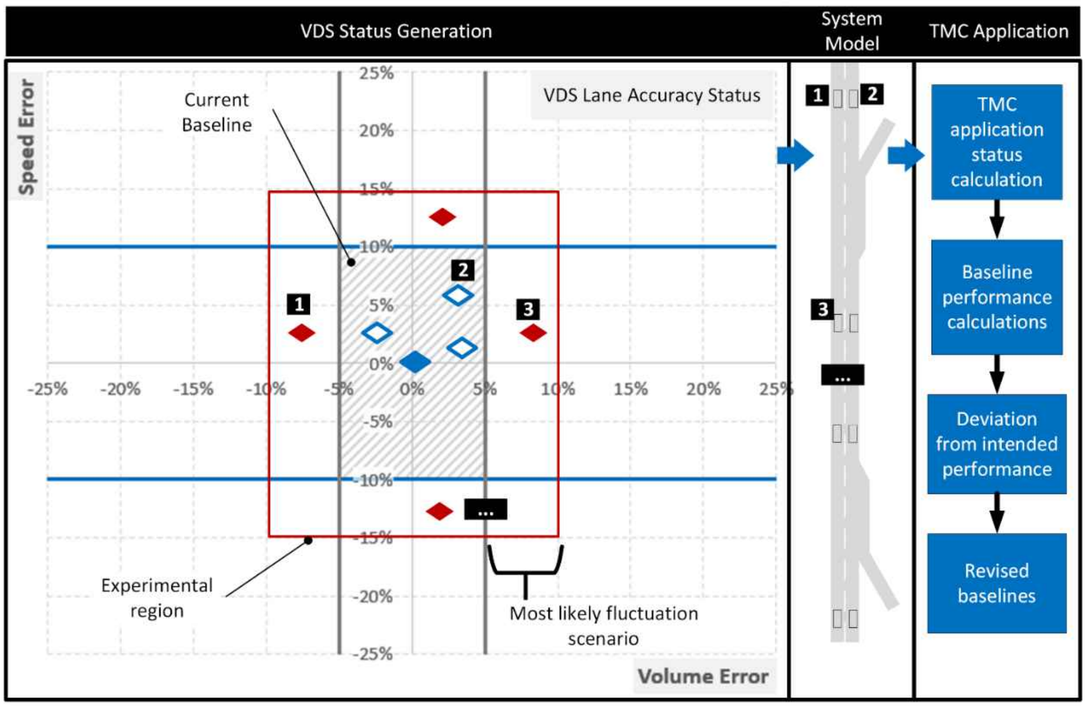


Figure 35: Overview of TMC Application Requirements Determination Process

1.4 Data-Driven Detector Simulation

Detector fluctuations were modeled using observed field behavior from the I-95 sample. The data were carefully collected and validated using video analysis and a synchronization procedure. In addition, the observed behavior is accurate and consistent. This means that, on average, the behavior matches the ground truth and it has low variability. The distribution of the error was analyzed and it fits to a normal distribution. The mean of the observed error was -0.011 and the confidence interval for the mean ranges from -0.0304 to 0.00789. Since 0 is part of this confidence interval then it is possible that the selected sample came from a distribution whose mean could be 0. This is also regarded as white noise. The final reason to select this behavior is that it is achievable by VDS in the field. The observed distribution was used as the random process that generate the detector fluctuation. A systematic failure is then induced such that the mean is displaced. This displacement occurs only in one direction at the time as indicated in Figure 39.

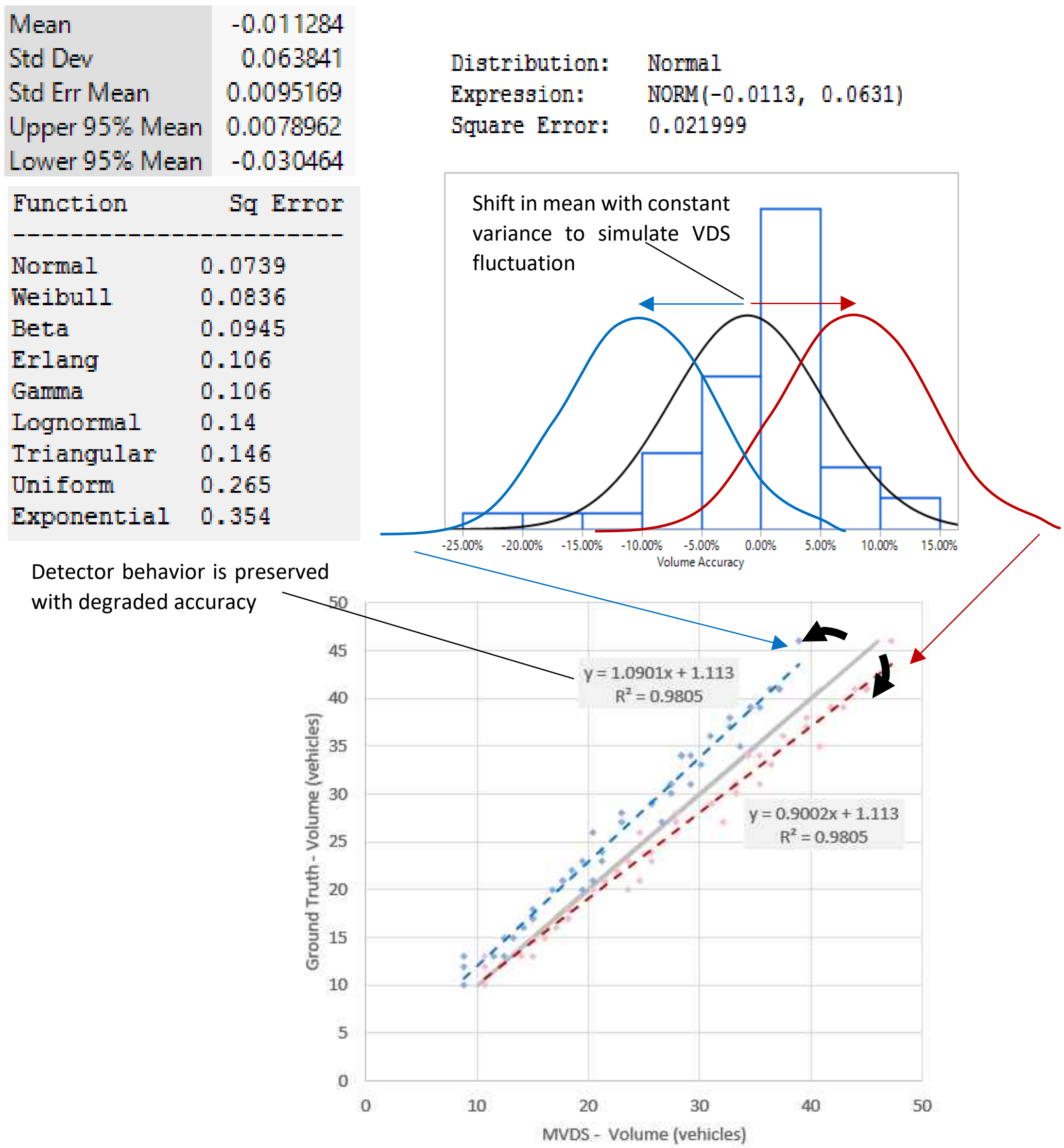


Figure 36: Overview of the Detector Fluctuation Simulation Procedure

Speed fluctuations were also observed in the field and taken into consideration for modeling and analysis. Figure 37 presents a histogram of the errors observed for speed fluctuations. There seems to be a systematic effect to overestimate speeds. This may have an adverse effect depending on the application. However, the speed fluctuations were below the allowable variation of 10 percent.

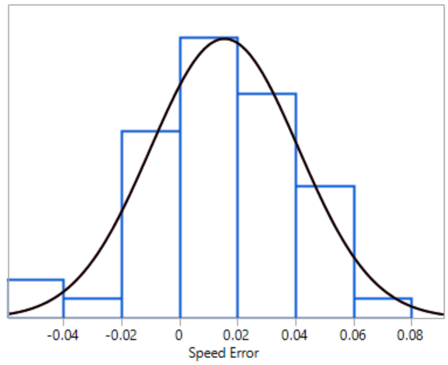


Figure 37: Observed Speed Fluctuations

1.4.1 Travel Time Posting

Travel time is calculated by an application running in SunGuide. Although there are several sources of data for travel time, VDS still the prime source for traffic monitoring information.

1.4.1.1 Process Mapping and Decision Making

Travel times are calculated on a per link basis. Usually there is one detector per link and the link length could be of variable length. Speed is calculated as a volume weighted average for the link. For a travel time all the individual link travel times are added as indicated in

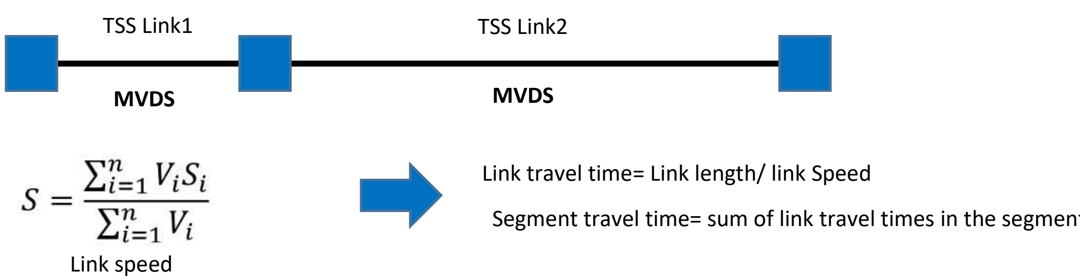


Figure 38: Link Travel Time Calculations

1.4.1.2 Effect of Accuracy Fluctuations

The amount of modeling possibilities is extensive. For the case of travel time calculations, the focus was to initially set experiments within the compliance area for speed and volume. This reflects the natural allowable fluctuation in the accuracy of the device as intended in specification 786. Using 20-second intervals data derived from field observations, a data simulation procedure was performed to account for the effects of variability in the travel time estimation. A verification procedure was performed using a regression approach to ensure that the simulated data behave as the observed field data under normal or baseline scenario. The result of the verification analysis is presented in Figure 39. It can be observed that the simulated behavior is equivalent to the observed behavior in the field since the slope is close to 45 degrees (y=x) with low variability. The dataset presented in Figure 39 has an overall station accuracy of five percent.

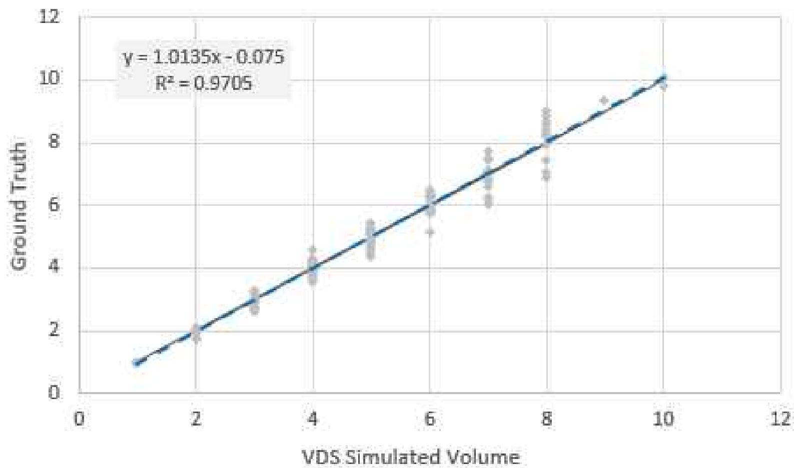


Figure 39: Volume Generation for Travel Time Application-Baseline Scenario

Travel time calculated over a one-mile segment aggregated in a 15-minute interval with for 20 simulation runs is presented in Figure 40 . It is observed that time aggregation has a significant impact on the stability of the estimate. It was also observed that under free flow conditions the error the of travel time estimates (0.85 minutes) is less than two percent. The estimates are lower than the ground truth due to the distribution of the speed variability, which presented a trend to be on the overestimating side but within the allowable limits (e.g., less than 10 percent).

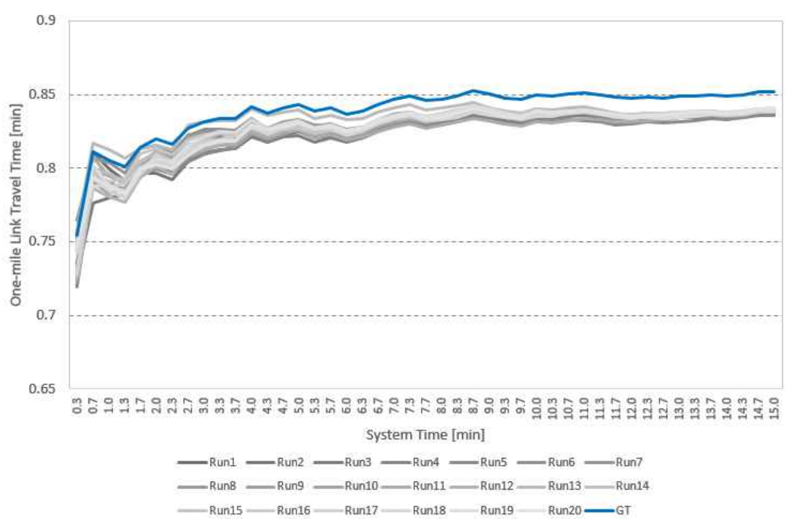


Figure 40: Travel Time Estimation-Baseline Scenario

A simulation centered in 0 for speed error is presented in Figure 41. It is observed that the estimate is in the middle of interval formed by the travel time estimates. This is a desirable behavior. However, given the low percentage of error, this is within acceptable limits.

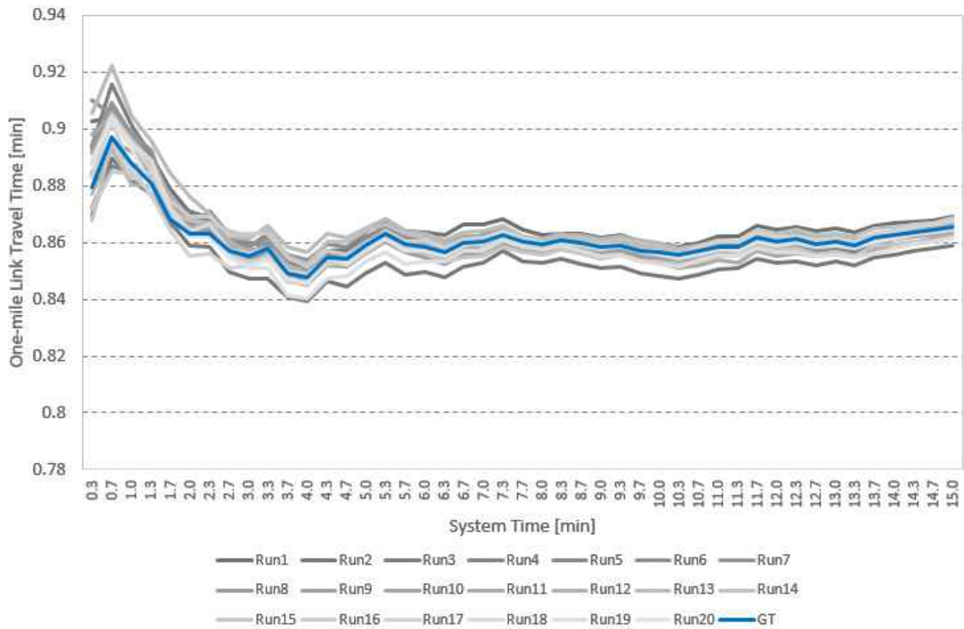


Figure 41: Travel Time Estimation with Centered Speed Error

A similar analysis was performed for the case of undercounting within 10 percent of the ground truth. In this case the VDS counts need to be multiplied by factors greater than one to reach the corresponding ground truth values. Figure 42 presents an instance of this scenario. It is observed that the regression line is above the identity equation y=x representing an undercounting fluctuation of less than 10 percent.

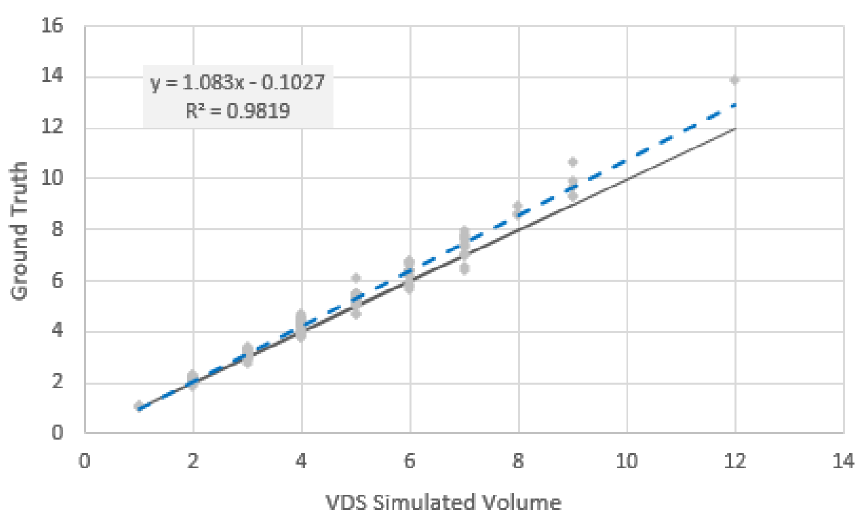


Figure 42: Volume Generation for Undercounting Scenario

In a similar fashion, the observed speed distribution played an important role in the visual behavior of the travel time estimation. Figure 43 shows how VDS data tends to underestimate ground truth estimate for travel time. However, the calculated error is less than two percent on the average cases.

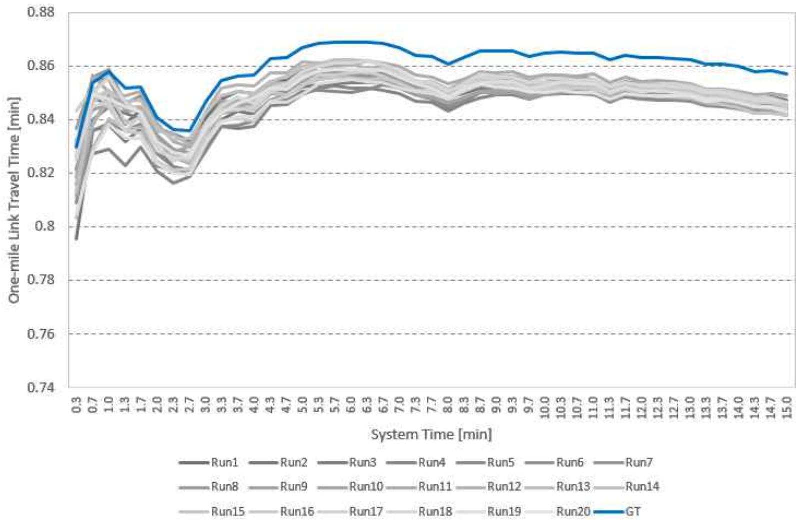


Figure 43: Travel Time Estimation for Undercounting Scenario

The last case to test on this particular application is the overestimation scenario at 10 percent error for volume. In this case one of the instances reached 87 percent for the overcounting behavior as observed in Figure 44.

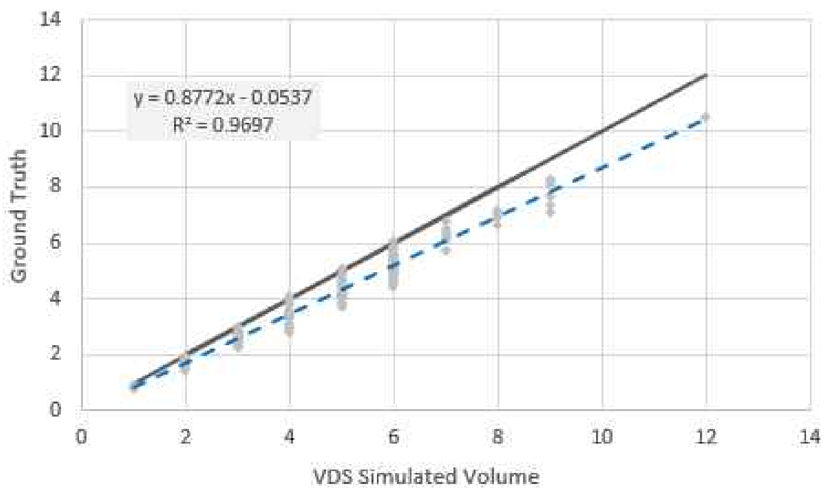


Figure 44: Travel Time for Overcounting Scenario

Travel time calculations were also not subjected to overcounting fluctuations having the estimation below two percent. This is in part due to the reduced amount of variability for speed in the selected detector sample. This procedure considers the case of the travel time estimation in steady state status. It is expected that larger error can occur when conditions drastically change (e.g., bottleneck).

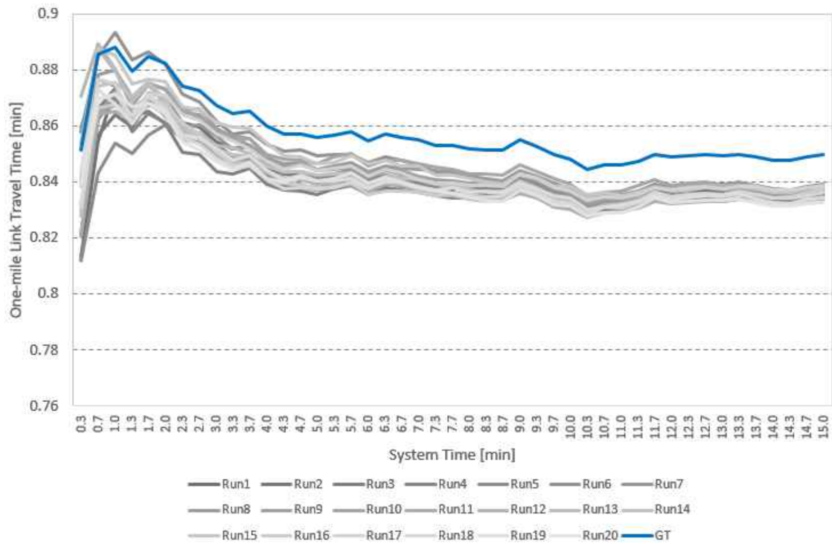


Figure 45: Travel time estimation-overcounting scenario

It is also important to note that the previous analyses were performed taken into consideration random fluctuations. In a random fluctuating, the detector can overestimate or underestimate by chance for any given time interval. Systematic detector fluctuations were also tested. A systematic detection fluctuation occurs when one or more detector accuracy fluctuates in one direction only (e.g., always overcounting). A scenario with a specific realization of systematic fluctuation is presented in Figure 46. The estimation error with respect to the ground truth in this case was three percent.

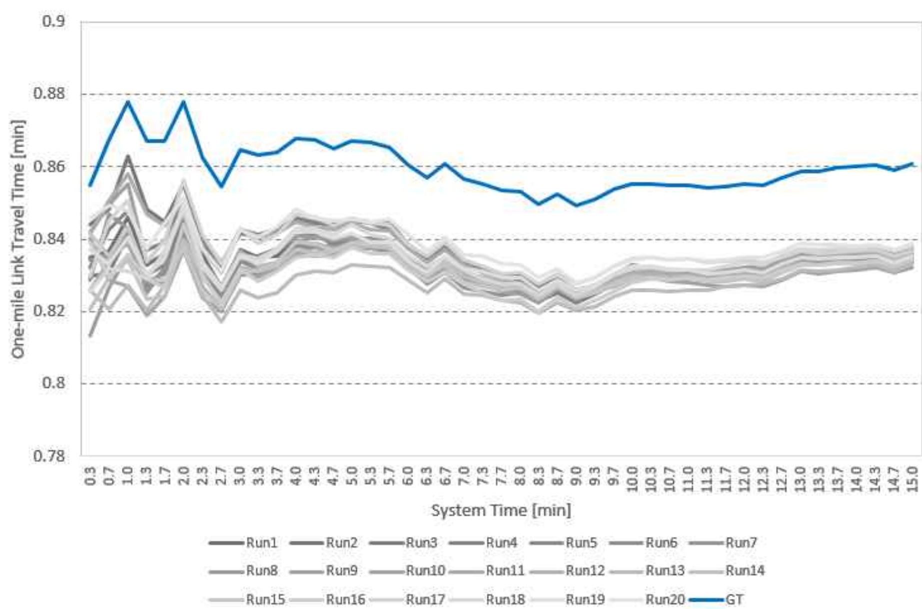


Figure 46: Travel Time Estimation-Systematic Fluctuation

Travel time calculation is in general unaffected by accuracy fluctuations, especially in free flow conditions. Based on the observed fluctuations on speed accuracy, travel time may be underestimated. Comparing travel times with probe vehicle data are always useful to highlight possible detection errors.

1.4.2 Express Lanes

Express lanes are a cost-effective way to utilize existing capacity more efficiently by actively managing transportation demand. The tolls on the express lanes are change dynamically due to congestion effects in the surrounding facilities. The first express lanes in Florida were located in in Miami on the I-95 corridor. These express lanes are in expansion to continue north to Broward County.

1.4.2.1 Stakeholder Definition

There are several stakeholders in express lane applications. General purpose lane users and express lane users are the most direct stakeholders of the system. There are also control and maintenance personnel along with enforcement that complete the system. Roadway users are directly affected by the express lane policies through the variable pricing. Pricing is varied in agreement with traffic conditions. Therefore, there should be a match between the toll price and the traffic conditions in the express lane facility.

1.4.2.2 Process Mapping and Decision Making

The relation between speed and volume must be calculated to define the traffic density (TD) that will be related to the LOS. The common approach is to define the rate for the sampling period, grouping the data in intervals, N being the total of vehicles detected within the sampling period (volume) the traffic density is given by the following expression.

$$TD = \frac{\sum_{i=1}^{N} Vehicle_i}{\left(\frac{\sum_{i=1}^{N} Speed_{Vehicle_i}}{N}\right)}$$

From the definition above, the toll rate change procedure is derived. The first step is to calculate the change in density (TD) given in the expression for ΔD below, where TD_t and TD_{t-1} are the traffic density at time interval t and $t-1$.

$$\Delta D = TD_t - TD_{t-1}$$

The next step is to look for the toll adjustment ($\Delta\tau$) value in a preset table similar to the excerpt in Figure 47

LOS	Traffic Density	Change in Traffic Density (TD)			
		-6	-5	...	-1
A	0	-$0.25	-$0.25		-$0.25
	1	-$0.25	-$0.25		-$0.25
	2	-$0.25	-$0.25		-$0.25
	3	-$0.25	-$0.25		-$0.25
⋮				⋱	⋮
F	> 45	-$2.00	-$2.00	...	-$0.50

Figure 47: Excerpt from: Toll Setting Table of I-95 Express Florida

In the sequence the new toll rate (τ_t) is calculated as given by (1) and the final toll amount is determined based on the constraints presented in (4) such that the minimum and maximum toll rate allowed within each LOS is observed.

$$\tau_t = \tau_{t-1} + \Delta\tau \qquad (1)$$

$$\tau_t = \begin{cases} \tau_{max}(D_t), if\ \tau_t > \tau_{max}(D_t) \\ \tau_{min}(D_t), if\ \tau_t < \tau_{min}(D_t) \\ \tau_t, otherwise \end{cases} \qquad (2)$$

The main inputs necessary to perform the procedure are the LOS settings (ranges of traffic density defining each LOS), the toll rate for each LOS and the traffic data from VDS (volume and speed), allowing the calculation of traffic density.

1.4.2.3 Effect of Accuracy Fluctuations

Express lanes rely on traffic density calculations. Experiments under the baseline conditions were performed. In order to facilitate interpretation of results, all calculations were applied on a one-mile segment. Density was accumulated and averaged on a 15-minute interval. The result was 13.68 vehicles per minute (VPM) for ground truth conditions and for the average of the remaining runs with random fluctuations it was 13.34. This gives an error of 2.5 percent. The estimation and stabilization of the 15-min average traffic density is presented in Figure 48.

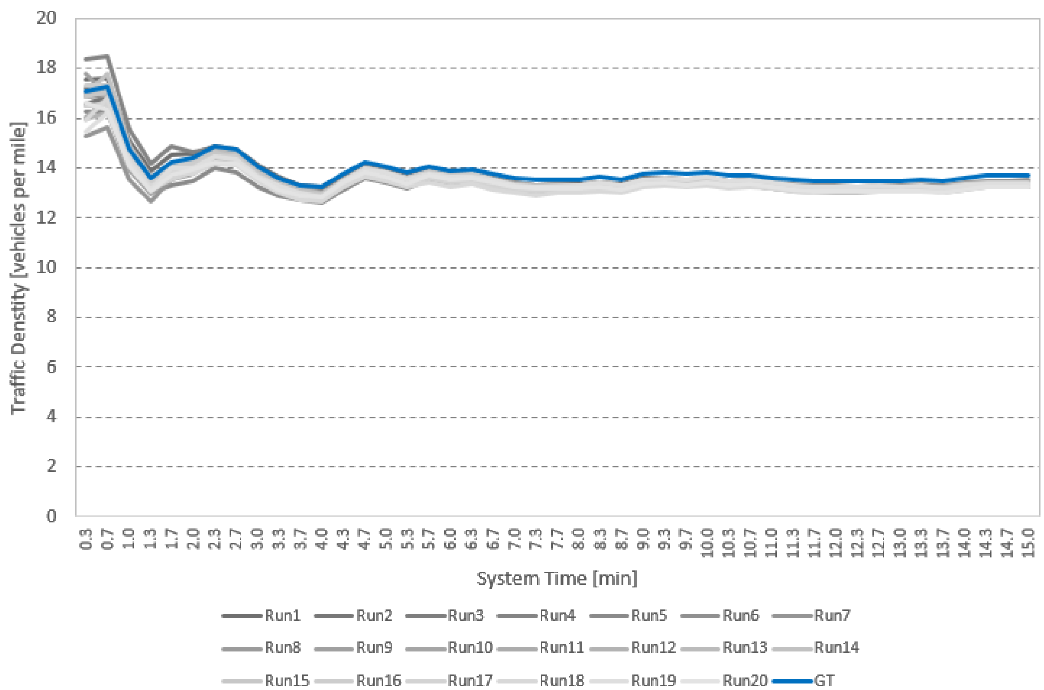


Figure 48: Traffic Density Estimation for Baseline Conditions

A scenario with random speed fluctuations and overcounting within 10 percent is presented in Figure 49. In this case there is a trend to overestimate traffic density. Overcounting was seven percent resulting in a 4.73 percent estimation error for traffic density.

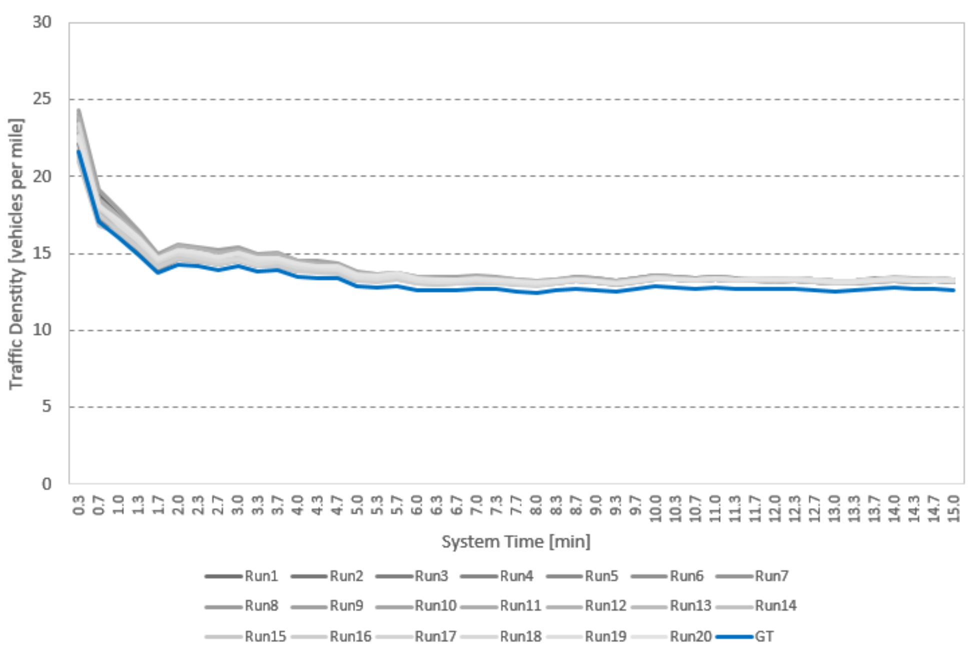


Figure 49: Traffic Density Estimation for Overcounting Conditions

The case of undercounting is presented in Figure 50. This case presents a significantly visible underestimation of the traffic density. This is mainly the mathematical effect of having less volume in the numerator and more speed in the denominator for the traffic density estimator. The error is 15 percent which translates to 2-3 vehicles. This could be the difference between two level or service categories for toll collection. In addition, the toll management system may not sense the congestion in time to take proper action.

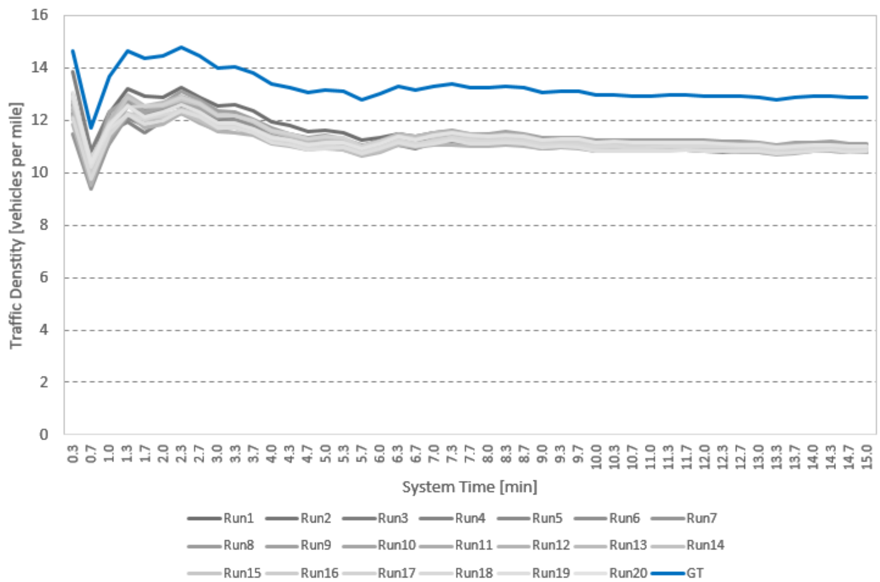


Figure 50: Traffic Density Estimation for Undercounting Conditions

1.4.3 Performance Monitoring

Performance measures provide an assessment of how well the traffic agencies are meeting its goals and mission statement. When reporting the status of the ITS program from the perspective of the traveling public, the performance measure programs are designed to further communication between system operators and users. In addition to providing accountability to the public, it also gives system managers the ability to better understand capabilities and areas for improvement in the currently deployed system to better allocate resources.

Within the performance monitoring scope is also the need to indicate the effectiveness of the ITS program. This is achieved through information about how efficiently the system uses its resources to generate goods and services as outputs. The quality of these outputs is also considered, taking into account how it is delivered to the stakeholder and the level of satisfaction generated by it.

1.4.3.1 Stakeholder definition

The main stakeholder of the performance monitoring application is the TMC management and staff who are responsible for all traffic management related to and supported by ITS systems. The information obtained by a comprehensive performance measurements program further improves a series of decision making process, including but not limited to: installation and maintenance resource allocation, expansion of system coverage, and incident response.

The Florida Transportation Commission (FTC) is, at the statewide level, in charge of evaluating the performance and management of the department of transportation, and can also be considered a stakeholder. Performance measures used at the district levels are defined to meet objectives of the statewide level.

The general traveling public is also affected by the performance monitoring process, relying on the maintenance of a good level of service and active management from the traffic management agencies to effectively act on areas where performance needs to be improved.

1.4.3.2 Process Mapping and Decision Making

The performance monitoring process is responsible for assessing information on the system level in order to evaluate general performance as a whole. This process also obtains specific information at a deeper level of details. The scope includes measurement of quantities of items, area of coverage, traffic flow, traveler information, equipment availability and performance. The process assesses how efficient the system is to convert resources into a relevant output. In the sequence measure types on the system level are presented, including congestion measures, travel time reliability, incident duration, and customer satisfaction.

Congestion Measures capture average congestion conditions in a segment relying on travel time information. The metrics require speed and volume data from VDS, and information on the length of the segment. The Travel Time Index is obtained from a ration of the average travel time for a segment to the segment free flow travel time. Travel time index (TTI) is applicable for a specific road section within a time period. For several road sections and time periods, the total traffic volume and the length of the segments are included to calculate a weighted average index ($\overline{TTI}$), as shown in the following expression:

$$TTI = \frac{TT}{TT_{freeflow}} \qquad \overline{TTI} = \frac{\sum_{i=1}^{n}(TTI_i \times VMT_i)}{\sum_{i=1}^{n}(VMT_i)}$$

Travel time reliability measures can be obtained using Planning Time Index and Buffer Index, for example. In both cases, the necessary data includes speed and volume data from VDS, and information on the length of the segment. The Planning time Index indicates the variability of roadway congestion, using the 95^{th} percentile travel time, while the Buffer Index reflects the extra time that added by most travelers to the average expected travel time.

Another important set of metrics is related to incidents, capturing incident conditions and delay effects. The Total Incident Duration is a metric that can be broken down in several smaller pieces: Detection Period, Verification Period, Response Period and Clearance Period. The delay due to incidents is also quantified per lane and secondary accidents due to congestion from the main event are also taken into consideration.

The customer satisfaction is generally assessed using surveys that range from overall ITS program questions to more specific items such as satisfaction with traveler information systems and traveler websites. A benefit/cost ratio can also be used to estimate ITS benefits (i.e., travelers and freight saved time, crashes reduced) in comparison with total ITS program cost.

1.4.3.3 Effect of Accuracy Fluctuations

Accuracy fluctuations for performance monitoring are related to travel time. It was previously shown that travel time estimation was robust against natural variation on VDS accuracy. The majority of the performance indicators involve a form of travel time or volume. Figure 51 presents a plot of the travel time index. It is observed that it illustrates a similar behavior to the travel time plot. In the case of the travel time index, the plot is scaled by dividing by the free flow travel time. The plots cannot be compared because they are derived from simulations and from different random data streams. Travel time index presents a similar degree of error with respect to the ground truth of less than two percent.

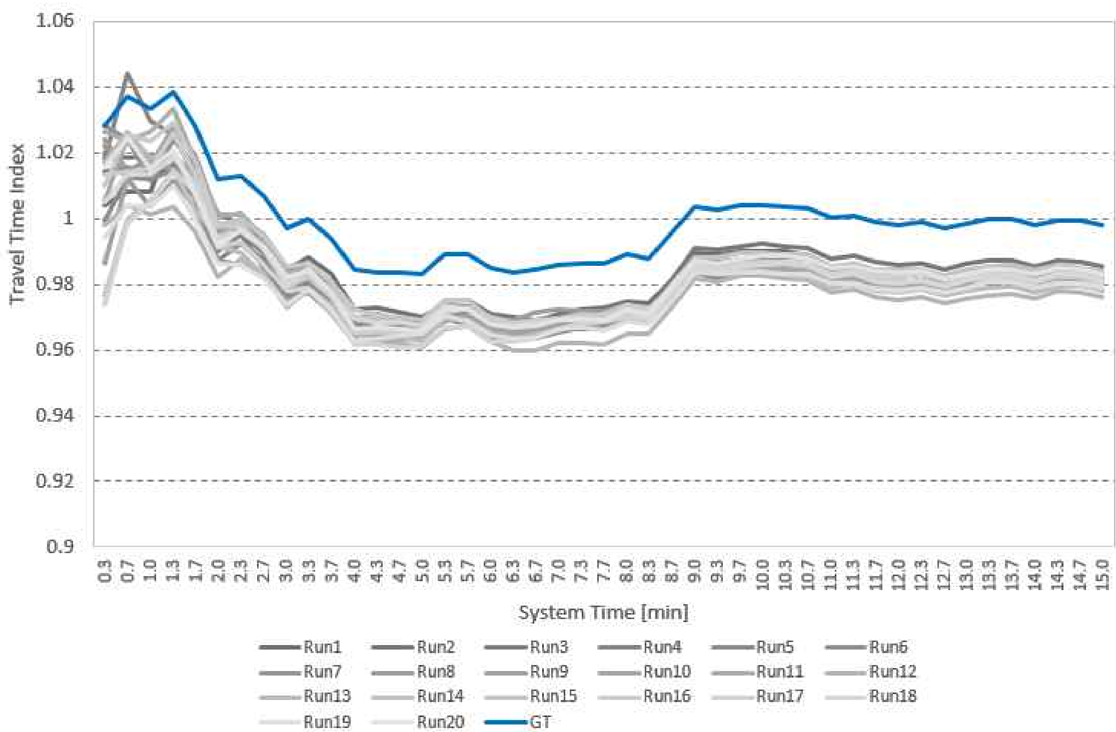


Figure 51: Travel Time Index Estimation for Baseline Conditions

1.4.4 Ramp Metering

Ramp metering relies on VDS occupancy, presence, and passage detectors for its correct operation. The basic algorithm for ramp metering is ALINEA. In ALINEA the metering rate is controlled by

$$r(k) = r(k-1) + K_r(\rho^* - \rho_s)$$

Where $r(k)$ the metering rate for ramp inflow is, K_r is regulator gain and ρ_s is the segment density. The parameter ρ^* is the reference density or control set point. In general, an estimation of the critical density is used as reference density. From the metering rate calculation, it can be observed that fluctuations in the metering rate are subject to a similar effect as the express lanes when density is use in the controller.

5 Causes of Variation of VDS over Time

In this chapter, data collected in several districts was analyzed to assess possible causes of VDS data quality variation over time. First, a set of performance metrics were defined and described. Samples of VDS and ground truth values were measured and analyzed. Current testing methods are also analyzed with the objective of proposing alternate testing methodologies and control strategies.

5.1 Performance Metrics

The performance metrics for VDS used in this report are grouped as system diagnosis, accuracy, consistency, and system availability. System diagnosis is related to aspects of hardware-software interaction on the containing system (SunGuide®) that can affect VDS performance. Accuracy and consistency are related to VDS measurement being close to the actual traffic variables and these are based on the technology and design of the device. System availability is related to the uptime and downtime of the VDS device and it is the result of the interaction of the reliability of the device and the system maintenance.

5.1.1 System Diagnosis

System diagnosis is based on the preconditions that the system components are powered, and communication is operational. It is intended to detect data quality errors that are the result of processing steps (software) or components operating in erroneous mode (hardware). The intention of diagnosis is to serve as an audit tool to detect configuration issues. Such configuration issues are avoided by carefully following VDS installation procedures recommended by the VDS manufacturers.

5.1.2 Raw Data Quality

Data quality tests are based on other detectors and data consistency checks. A comprehensive list of VDS quality tests can be found in (*40*). Data quality tests as those listed in the Regional Integrated Transportation Information System (RITIS) were applied to the raw data as a measure of verification. The output of the application of data quality tests is the percentage of intervals with consistent data.

5.1.3 Data Reads

This checking procedure ensures that detection data are being polled at the specified rates by the data handling subsystem. For example, if the cycle time is intended to be 60-second intervals, it is expected that each hour of data should contain about 60 timestamped records of reported volumes, speeds, and occupancy. Minor discrepancies may occur due to synchronization. Following the same logic, each day should have 1,440 records for each lane. Variation on these lane readings can occur. The output of this metric is the number of reads in a predetermined time interval (e.g., 15 minutes). If this number beyond a certain threshold (e.g., 5%) with respect to its expected value, it is an indication of a system malfunction.

5.1.4 VDS Synchronization

Time synchronization refers to how data patterns observed in the field are logged by the VDS on a consistent timeframe. It is expected that two VDS co-located will record similar traffic patterns for the same time period. For applications requiring data from several VDS over short time intervals, a high degree of synchronization is desirable. The timeframe for all VDS retrieved data are the same since the data handling systems provide the timestamps for raw data intervals. However, in the field each detector records and stores data until the data handling system is ready to retrieve them. This may induce a time lag between the actual interval time and the system timestamp. This is the result of software-hardware interactions.

5.1.5 Accuracy

Accuracy is defined as the degree of agreement between a VDS measurement and a ground truth or reference value. The difference between the measure value and the reference value is known as bias. Bias can be corrected via calibration.

5.1.6 Consistency

Consistency is defined in this project as the variability of the VDS when presented with same conditions multiple times. In quality engineering terms, this is referred to as precision, repeatability, or short-term variability (*41*). The measure of consistency is the standard deviation. Consistency is a characteristic of the measuring device and cannot be corrected via calibration (assuming the device was installed following manufacturer's recommendation).

5.1.7 System Availability

System availability is the probability that a VDS is performing as intended at a given point in time when operated and maintained as per manufacturer's recommendations. It is an overall measure of the reliability and maintainability of the component or system. The historical system availability has two components uptime, and downtime and it is defined as:

$$Availability = \frac{uptime}{uptime + downtime}$$

Other related measures include mean time between failures (MTBF), mean time to repair (MTTR) and mean time between maintenance (MTBM). The availability concept can be extended beyond the device level by specifying the scope of the operation. If the VDS operations include aspects possibly attributable to external system (e.g., data reads) the concept of availability will cover device hardware and software.

5.2 Field Data Analysis Using the I-95 Vero Beach, FL, Data Set

The selected segment is about nine miles long, between miles 138 and 147 on I-95. Bounded north by the State Road 60 and south by the State Road 614, the segment was chosen taking into consideration some desirable characteristics. The segment has no entry or exit points, so it is safe to assume conservation of vehicle flow through the system. Speed fluctuation is also minimized since changes in acceleration due to vehicles entering or exiting the system are not present. The segment contains nine detection stations, distributed roughly one mile apart. Each station is equipped with Wavetronix SmartSensor HD microwave detectors, as shown in. Figure 52

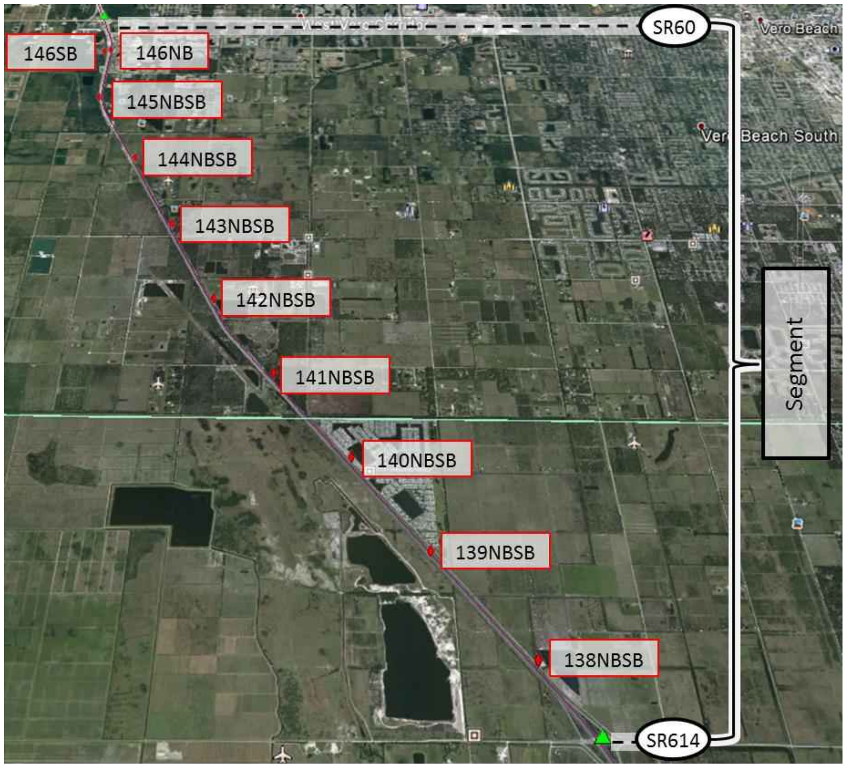
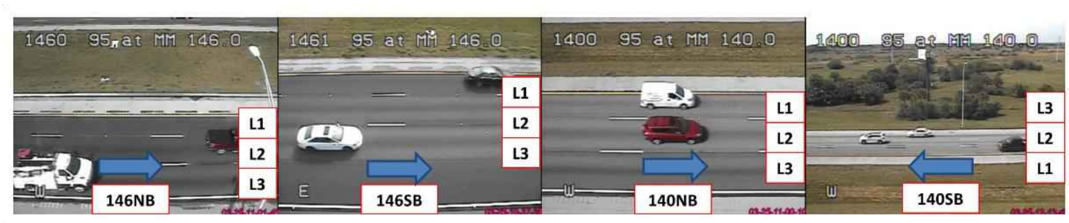


Figure 52: Data Collection Site: I-95 from Mile Post 138 to 147

Out of the nine stations, eight have a single MVDS pointed at both directions of traffic. The tags in Figure 52 reflect that fact by showing “NBSB” to indicate that both directions are covered by the detector. The only exception is at the station located at mile post 146, where there are two MVDS, each one responsible for one direction of traffic. The segment also has traffic cameras, installed at the same posts, on a higher position in relation with the collocated MVDS.

In order to estimate the ground truth data, the cameras located at the mile posts 140 and 146 were selected and video was recorded for processing and posterior data reduction. Figure 53 shows the view from the three selected traffic cameras. Figure 53(a) view is from the camera located on the pole in the northbound side of I-95, while Figure 53 (b) is located in the pole in the southbound side, both at mile post 146. Figure 53(c) and Figure 53(d) are from the same camera, with different angle and tilt parameters. The direction of the traffic flow is indicated in the figure with blue arrows. The lane numbering scheme is indicated in Figure 53 and as a rule, the numbering always starts from the mid-section of the road, with numbers ascending from left shoulder to right shoulder.



(a) (b) (c) (d)

Figure 53: Traffic Cameras Views

5.2.1 Data Collection and Processing

The data collection performed on March, 25th 2016, between 10:30 am and 1:30 pm, was designed so the team could obtain two sources of data to be analyzed. The main interest was to gain insight in the accuracy of VDS data. The usual approach is to select a test site where the VDS of interest is collocated with loop detectors, so the latter is assumed to provide ground truth data. This approach reduces the data processing needs, since the task of obtaining ground truth data are simplified. The down side is that the approach constraints the study to locations where loop detectors are available. To avoid this constraint, this study uses traffic camera video as the source of ground truth data to be compared to the VDS data available in SunGuide.

5.2.1.1 Ground Truth Data Source: Traffic Camera Video

The team was divided in two fronts to be able to collect all necessary data. During the data collection, one team member was in charge of the video recording equipment setup for the chosen traffic cameras in the TMC in Fort Lauderdale, FL. Two other team members were responsible for generating probe vehicle data to be used for video calibration.

The probe vehicle data were obtained by driving two identical vehicles within the segment during the video recordings. Each probe vehicle was driven by each lane once, passing in front of the traffic cameras with known speed. To better understand the data collection process, let's consider that, from Figure 52, State Road 60 is point A and State Road 614 is point B. Since there are three lanes of traffic to cover in each direction, each probe vehicle was driven from point A to point B three times and from point B to point A another three times, summing up to a total of six runs. Each direction of traffic has two cameras of interest, so each run generates two video files, one for each camera. Table 15 below summarizes the run orders with the respective video numbers generated. For future reference, a video name is also attributed to each video, indicating the Camera ID, the direction of flow and the run number, in that order.

Table 15: Data Collection Scheme

		Lane 1		Lane 2		Lane 3	
		Cam.146	Cam.140	Cam.146	Cam.140	Cam.146	Cam.140
SB	Run Order	1^{th}	1^{th} [1]	3^{rd}	3^{rd}	5^{th}	5^{th}
	Video No.	1	2[1]	5	6	9	10
	Video Name	146SB_R1	140SB_R1[1]	146SB_R3	140SB_R3	146SB_R5	140SB_R5
NB	Run Order	2^{nd}	2^{nd}	4^{th}	4^{th}	6^{th}	6^{th}
	Video No.	4	3	8	7	12	11
	Video Name	146NB_R2	140NB_R2	146NB_R4	140NB_R4	146NB_R6	140NB_R5

1 – The video could not be recorded; consequently no ground truth was obtained for that interval.

During the entire data collection the traffic was in free-flow condition, so it was expected that the travel time per run would be around seven minutes. To ensure that both probe vehicles would be recorded in each run, the team recorded around 10 minutes of video per run for each camera involved in the run. The probe vehicles were used to calibrate the videos before processing, so the video data reduction process would be able to generate the ground truth volume, speed, and classification. Both probe vehicles' dimensions were measured and prepared to be easily identifiable in the video, using two 2 ft. by 1 ft. 6 in. stickers in each side and on the top of the vehicle.

Besides providing dimensions, the probe vehicles also reported GPS data for the entire length of the experiment. Knowing the dimensions of the vehicles and the speed they passed in front of the traffic camera, the video calibration was done per lane, as exemplified in Figure 54. The software used for video analysis is Kinovea (*42*).

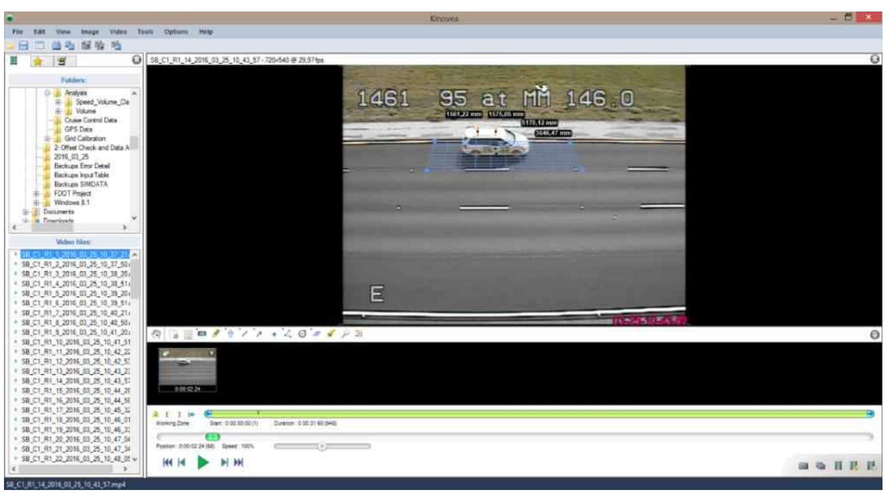


Figure 54: Video Calibration Using Probe Vehicle Data

The known vehicle dimensions were used as base for the grid positioning and dimensioning in each lane. In the sequence the vehicle was tracked using the software to obtain a measurement of speed. The speed values obtained from the software were then compared to the known speed from the GPS data, and the offsets between the two data sources were used as feedback to further optimize the grid configuration. The reason why the calibration was optimized for speed is in the nature of the SunGuide reported data (lengths are reported in pre-defined ranges, while speeds are reported as continuous data). Table 16 presents the remaining error after completing the calibration, showing speed error ranging from -0.86% to 1.37% with an absolute average of0.33%, when compared to GPS speed data.

Table 16: Calibration Error

Camera	Probe Veh. No.	Lane	Run	Speed [mph]		Error
				GPS	Kinovea	
146SB	1	1	1	66.91	66.77	-0.21%
146SB	2	1	1	63.62	63.68	0.09%
146SB	1	2	3	70.75	70.88	0.18%
146SB	2	2	3	67.00	66.55	-0.67%
146SB	1	3	5	65.92	66.29	0.56%
146SB	2	3	5	68.19	67.93	-0.38%
146NB	1	1	2	N/A[1]	N/A[1]	N/A[1]
146NB	2	1	2	N/A[1]	N/A[1]	N/A[1]
146NB	1	2	4	N/A[1]	N/A[1]	N/A[1]
146NB	2	2	4	N/A[1]	N/A[1]	N/A[1]
146NB	1	3	6	N/A[1]	N/A[1]	N/A[1]
146NB	2	3	6	N/A[1]	N/A[1]	N/A[1]
140SB	1	1	1	N/A[2]	N/A[2]	N/A[2]
140SB	2	1	1	N/A[2]	N/A[2]	N/A[2]
140SB	1	2	3	70.89	70.72	-0.24%
140SB	2	2	3	69.89	70.09	0.29%
140SB	1	3	5	67.91	67.98	0.10%
140SB	2	3	5	67.28	68.20	1.37%
140NB	1	1	2	70.89	70.86	-0.04%
140NB	2	1	2	70.86	70.25	-0.86%
140NB	1	2	4	68.90	68.92	0.03%
140NB	2	2	4	69.04	69.02	-0.03%
140NB	1	3	6	70.44	70.46	0.03%
140NB	2	3	6	70.60	70.46	-0.20%

1 – Due to a SunGuide technical problem no data were reported for that interval. Calibration was not performed since there was no data available to compare to.
2 – The video indicated could not be recorded; consequently no ground truth was obtained for that interval.

The video data collection resulted in three hours, 26 minutes and 26 seconds of video for all of the 4 camera views. Table 17 below presents the detailed information for each video file, including the length of each video, time intervals and amount of data processed for volume and speed. As discussed in previously, no VDS data were reported by SunGuide for the intervals corresponding to the 2nd, 4th, and 6th runs for camera 146NB. For that reason the equivalent one hour, 19 minutes and 32 seconds of video weren't analyzed, since there was no VDS data to compare.

For volumes, the data gathered was grouped in 10-minute intervals. The speed data intervals were defined to include the probe vehicle drive-by within the analyzed period. Out of the remaining two hours, six minutes and 54 seconds of available video data, one hour and 40 minutes of video were processed to generate volume ground truth data and 40 minutes of video were processed to generate speed ground truth data.

Table 17: Video Processing Detail

	Video Length		**Volume Data**			**Speed Data**		
	From *(hh:mm:ss)*	**To** *(hh:mm:ss)*	**From** *(hh:mm:ss)*	**To** *(hh:mm:ss)*	Δt *(mm:ss)*	**From** *(hh:mm:ss)*	**To** *(hh:mm:ss)*	Δt *(mm:ss)*
146SB_R1	10:37:21	10:53:20	10:38:00	10:48:00	10:00	10:42:00	10:47:00	5:00
146SB_R3	12:12:39	12:25:23	12:13:00	12:23:00	20:00	12:14:00	12:19:00	5:00
146SB_R5	12:48:56	13:14:45	12:49:00	13:09:00	10:00	13:03:00	13:08:00	5:00
140SB_R1	-	-	-	-	0:00	-	-	0:00
140SB_R3	12:13:38	12:25:07	12:14:00	12:24:00	10:00	12:19:00	12:24:00	5:00
140SB_R5	12:51:13	13:14:46	12:52:00	13:12:00	20:00	13:10:00	13:15:00	5:00
140NB_R2	11:00:01	11:12:35	11:01:00	11:11:00	10:00	11:05:00	11:10:00	5:00
140NB_R4	12:29:14	12:41:52	12:30:00	12:40:00	10:00	12:35:00	12:40:00	5:00
140NB_R6	13:19:38	13:31:46	13:20:00	13:30:00	10:00	13:26:00	13:31:00	5:00
146NB_R2	11:01:44	11:13:32	-	-	0:00	-	-	0:00
146NB_R4	12:30:36	12:43:15	-	-	0:00	-	-	0:00
146NB_R6	13:21:08	14:16:13	-	-	0:00	-	-	0:00
				$\sum_{Volume} \Delta t =$	100:00		$\sum_{Speed} \Delta t =$	40:00

5.2.1.2 VDS Data Source: SunGuide Software

The second source of data comes from the SunGuide database. The data provided is grouped in 20-second intervals as shown in the excerpt presented in Figure 55. The content of each column is indicated in the figure and described in the sequence.

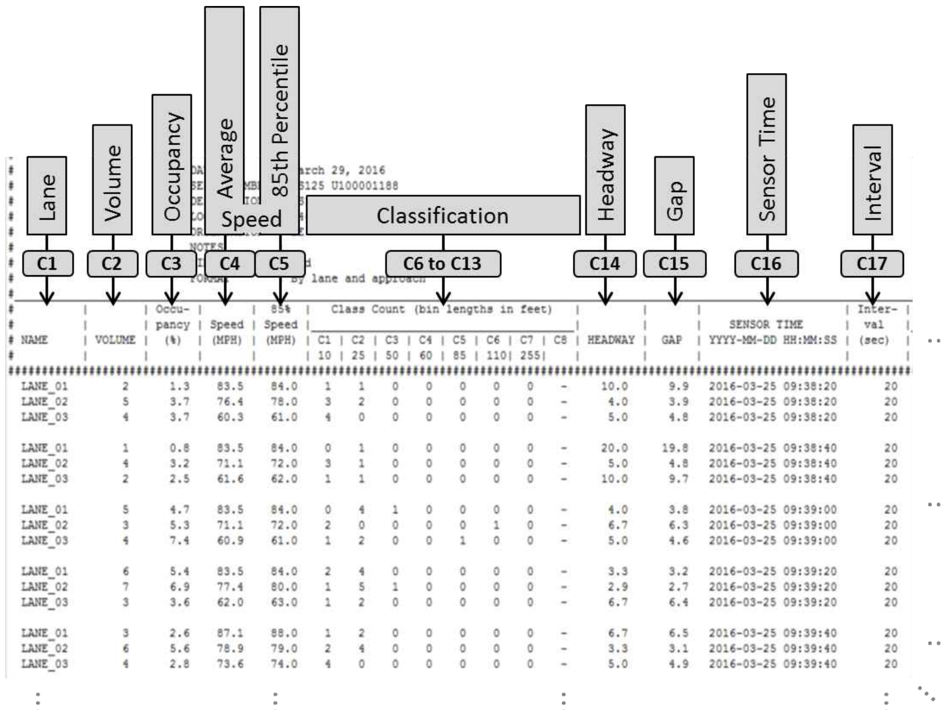


Figure 55: SunGuide Data Format

- Lane (Column 1): Sorts the data table by lane, presenting a sequence of all lanes being monitored. The data are organized by adding a blank row between lanes from different time intervals. The column can be considered as a secondary filter to order the data. The primary filter is column 16 Sensor Time.
- Volume (Column 2): Reports the sum of the vehicles per lane passing in the detection zone within each time period.
- Occupancy (Column 3): Reports the percent occupancy of the detection zone. The data in this column is given in percentage.
- Speed (Column 4): Reports the average speed per lane of the vehicles passing in the detection zone within each time period. The data in this column is given in miles per hour.
- 85th Percentile Speed (Column 5): Reports the 85th Percentile Speed that is given as the speed that 85% of vehicles do not exceed. The data in this column is given in miles per hour.
- Classification (Columns 6 to 13): The eight columns report vehicle length classification within pre-defined bins. Each one of the eight bins was pre-configured with a maximum length value in feet. As the vehicles pass within the detection zone, they will be classified in bins, giving that configuration. If for example, the first bin receives the value 10 feet and the second bin receives the value 25 feet, any vehicle with length ranging from 0 to

10 feet will be classified as category 1 vehicle, while vehicles ranging from 10 to 25 feet will be classified as category 2 vehicles. There are no universal standards to define the maximum length of each bin, so each detector should be analyzed independently.

- Sensor Time (Column 16): Reports the full date timestamp for the time period of time of the reported data. It is important to notice that, even though the column is named 'Sensor Time', the time stamped in this column comes from the SunGuide system, and not from the detector itself. Another important characteristic to notice is that the timestamp in this column refers the higher limit of the interval.

- Interval (Column 17): Reports the length of time in seconds of each data pulling interval.

When combined, the data from columns 16 and 17, give the time interval for each row of data. To exemplify, consider the first timestamp for column 16 from the excerpt: "2016-03-25 09:38:20". Since the interval in column 17 is given 20 seconds, the data in the first row was detected from 03/25/2016 09:38:00 to 03/25/2016 09:38:20.

Table 18 presents the available detector data. Three out of the ten files receive didn't include the necessary data. Taking a closer look at each one of the remaining files it was possible to notice that the 146SB data had some inconsistencies from 09:43:40 to 09:45:40. The inconsistencies indicate that the detector was recalibrating the internal lane configuration. During that period six lanes were reported before the VDS could correctly redefine the number of lanes.

Table 18: Available SunGuide Data

	Data Available		Includes Data Collection Period
	From *(hh:mm:ss)*	**To** *(hh:mm:ss)*	
146SB	03/25/2016 09:38:20 am	03/25/2016 04:00:00 pm	Yes
146NB	03/25/2016 09:39:00 am	03/25/2016 04:00:00 pm	Yes
145NBSB	03/25/2016 09:43:40 am	03/25/2016 04:00:00 pm	Yes
144NBSB	03/25/2016 09:43:40 am	03/25/2016 04:00:00 pm	Yes
143NBSB	03/25/2016 09:43:40 am	03/25/2016 04:00:00 pm	Yes
142NBSB	03/25/2016 03:59:40 pm	03/25/2016 04:00:00 pm	No
141NBSB	03/25/2016 09:44:00 am	03/25/2016 04:00:00 pm	Yes
140NBSB	03/25/2016 09:42:20 am	03/25/2016 04:00:00 pm	Yes
139NBSB	03/25/2016 03:59:00 pm	03/25/2016 04:00:00 pm	No
138NBSB	03/25/2016 03:55:00 pm	03/25/2016 04:00:00 pm	No

5.2.2 Exploratory Data Analysis

We begin the data analysis by addressing the way that VDS accuracy fluctuations occur, to gain insight on how the TMC applications will be affected. Our approach is to analyze the I-95 segment data set summarizing its main characteristics.

Equation below show the way the accuracy fluctuations are calculated for volume (indicated by Δ_V) and for speed (indicated by Δ_S), where V_{VDS} and S_{VDS} are, in that order, the volume and speed data given by the VDS, and V_{GT} and S_{GT} are, in that order, the ground truth volume and speed data obtained with the video analysis.

$$\Delta_V = \frac{V_{VDS} - V_{GT}}{V_{GT}} \qquad \Delta_S = \frac{S_{VDS} \times V_{VDS} - S_{GT} \times V_{GT}}{V_{GT}}$$

(a) **(b)**

The following charts present the accuracy fluctuations for each one of the indicated periods. The charts are presented per pair Camera/VDS and indicated using the name convention from Figure 52. The signs for accuracy were preserved to keep track of the direction of fluctuation. Negative values indicate that the VDS data from SunGuide is below the ground truth data. On the other hand, positive values indicate that the VDS data from SunGuide is above the ground truth data.

Figure 56 summarizes the accuracy fluctuation for volume. The horizontal axes are categorical, representing each one of the three lanes and the station (lanes combined). The time period for each interval is also given. The vertical axes are given in vehicle counts. Figure 57 summarizes the accuracy fluctuation for speeds. The horizontal axes are categorical, representing each one of the three lanes and the station (lanes combined). The time period for each interval is also given. The vertical axes are given in miles per hour.

The conclusions that can be draw from the charts, taking into account that the accuracy error acceptance standard for volume in Florida is $\pm 95\%$, are summarized as:

- VDS 146SB: In the first period, from 10:38:00 to 10:48:00, Lanes 1 and three would fail to meet the acceptance criteria. All lanes combined within this period would also fail. In the following three periods (from 12:13:00 to 12:23:00, from 12:49:00 to 12:59:00, and from 12:59:00 to 13:09:00) every lane individually, as well as the lanes combined within each period, would pass the acceptance test. One of the possible explanations for the error in the first period is that the detector went under self-calibration from 09:43:40 to 09:45:40. It is expected that some time would pass until the calibration reaches an optimum point. The approval rate would be 10 out of 12 lanes, or 83% of the tested lanes.
- VDS140NB: In the first period (from 11:01:00 to 11:11:00), lanes 1 and 3 would fail to meet the acceptance criteria. In the second period (from 12:30:00 to 12:40:00) lane 1 would fail to meet the acceptance criteria. In the third period (from 13:20:00 to 13:30:00), lane 1 and lane 3 would fail to meet the acceptance criteria. All lanes combined per period would pass the acceptance tests for all three periods. The approval rate would be 4 out of nine lanes, or 44% of the tested lanes.
- VDS 140SB: All lanes would be pass the test as well as all lanes combined within each period. The approval rate would be nine out of nine lanes, or 100% of the tested lanes.

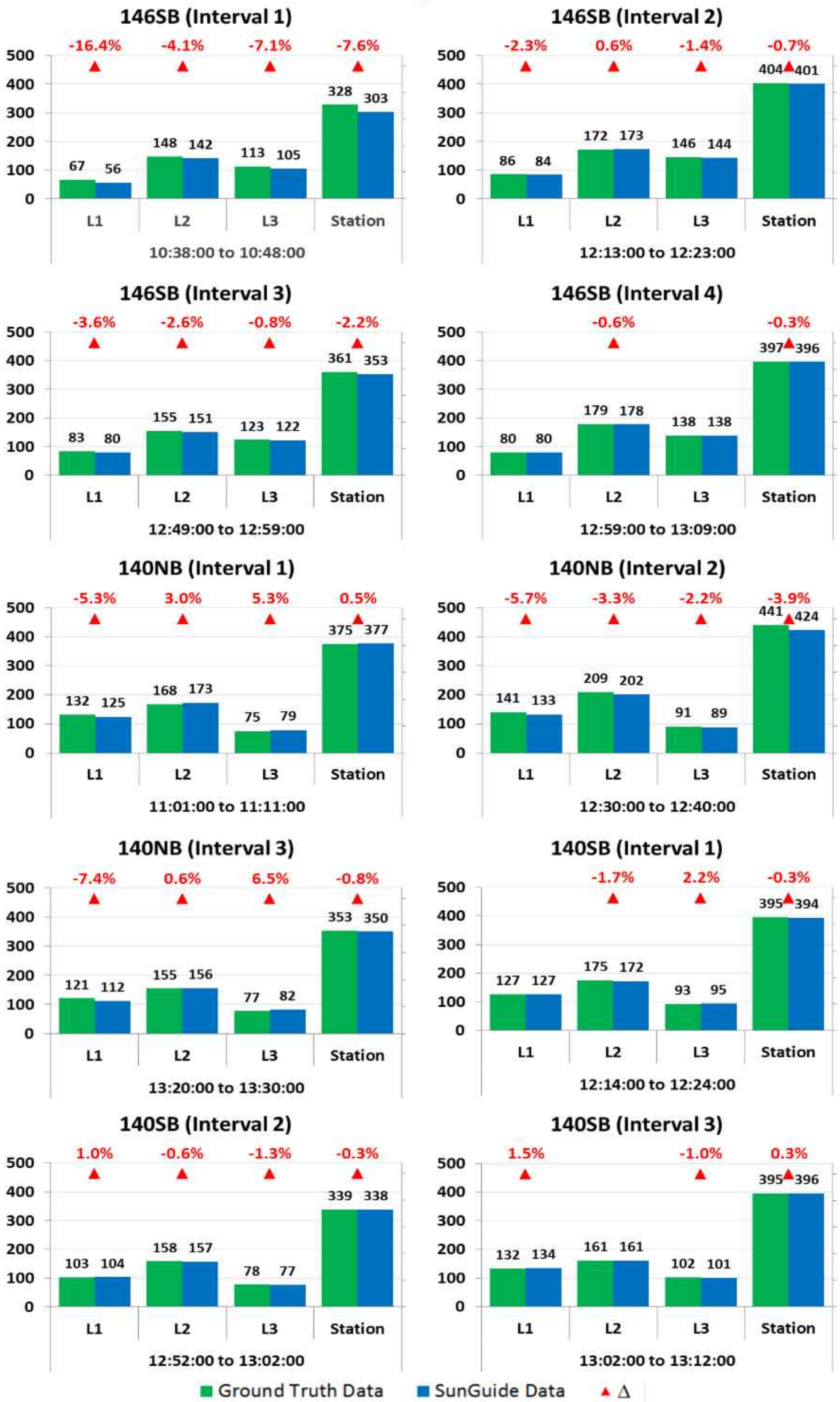


Figure 56: Volume Measurements Performance Error

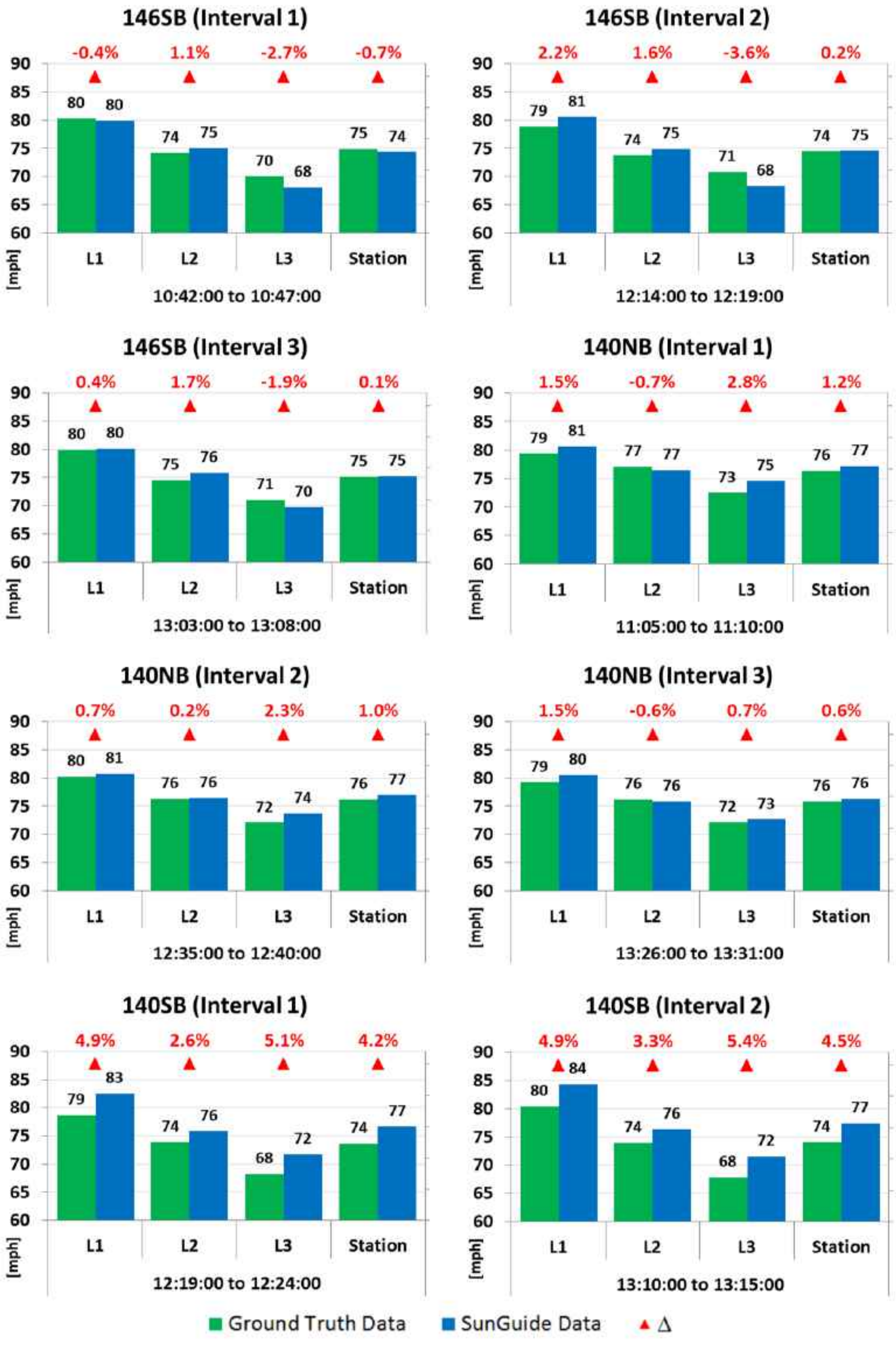


Figure 57: Speed Measurements Performance Error

Given that the accuracy error acceptance standard for speed in Florida is $\pm 90\%$, we can analyze the performance of each detector. The conclusions from the charts presented in Figure 57 can be summarized as:

- VDS 146SB: All lanes would be pass the test as well as all lanes combined within each period. The approval rate would be nine out of nine lanes, or 100% of the tested lanes.
- VDS 140SB: All lanes would be pass the test as well as all lanes combined within each period. The approval rate would be six out of six lanes, or 100% of the tested lanes.
- VDS 140NB: All lanes would be pass the test as well as all lanes combined within each period. The approval rate would be six out of six lanes, or 100% of the tested lanes.

In the sequence, a scatter plot was constructed, plotting speed percent error versus volume percent error (see Figure 58). Each point in the chart corresponds to a speed-volume error pair for a 5-minute data aggregation, following the minimum data collection period, as required by Specification 660 (*9*). The points in the chart are coded for easier visualization, where lane 1 is represented by triangles, lane 2 is represented by squares, and lane 3 is represented by the diamond shape. Each detector is also represented by a different color. The horizontal blue lines represent the accuracy requirements for speed (±10%), while the vertical gray lines represent the accuracy requirements for volume (±5%).

It can be observed by analyzing the charts from Figure 56, and Figure 57 that more relevant volume accuracy fluctuations are present while speed fluctuations are always within the tolerance limits. This can be generalized from Figure 58, based on the number of points outside the performance limits for volume (11 out of 24) while there are no points outside the performance limits for speed. Of the 11 out of specification points, there are five in the undercounting region and six in the overcounting region. It is noticeable that three out of the 11 out of specification points stand out (at the leftmost portion of the scatter plot). After conducting a more detailed analysis, it was determined that one 20 second data interval from detector 146SB was missing in the SunGuide database, generating the detected undercounts. Detector 140NB is responsible for seven out of the 11 non-compliant points. Out of the seven points, two are in the undercount region (both cases for lane 1), and five in the overcount region. Out of the five points in the overcount region, three are slightly over the acceptance criteria, at 5.1%, 5.3% and 5.4% error. Detector 140SB seems to be mostly within the performance limits, presenting one overcount in lane 3 with an error of 5.9%.

Another aspect of interest is verifying if the accuracy fluctuations occur independently by lane and by speed and volume errors. The correlation analysis, presented in Figure 59, gives a coefficient of 0.3756, indicating a weak relationship between speed and volume errors. In this case it can be assumed that speed and volume can fluctuate independently at the lane level. For example, any detector at any given point in time could be overestimating volume while speed estimation may be on target. There is no direct or inverse proportional relationship between speed errors and volume errors. These conclusions are going to be relevant during the process of modeling detector failures at the lane level to reflect the conditions encountered in the field.

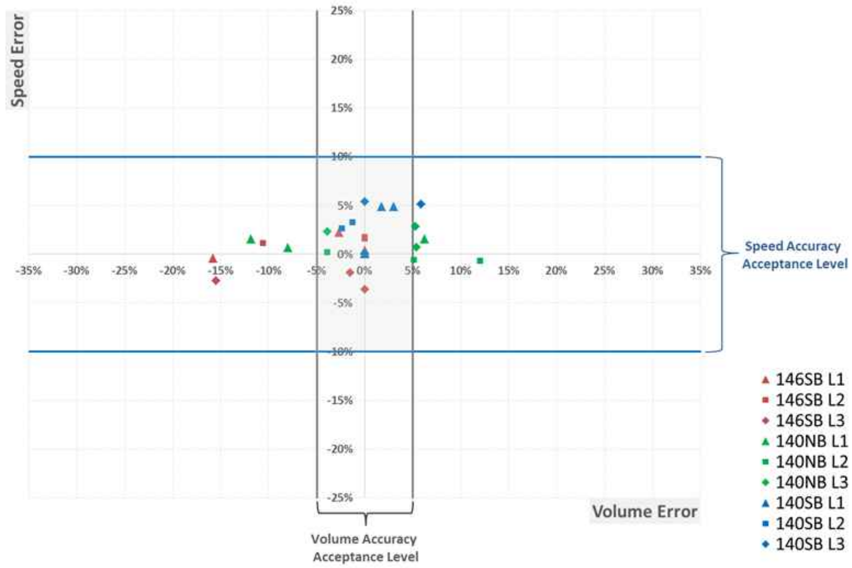


Figure 58: Scatter Plot: Speed and Volume Accuracy Fluctuation

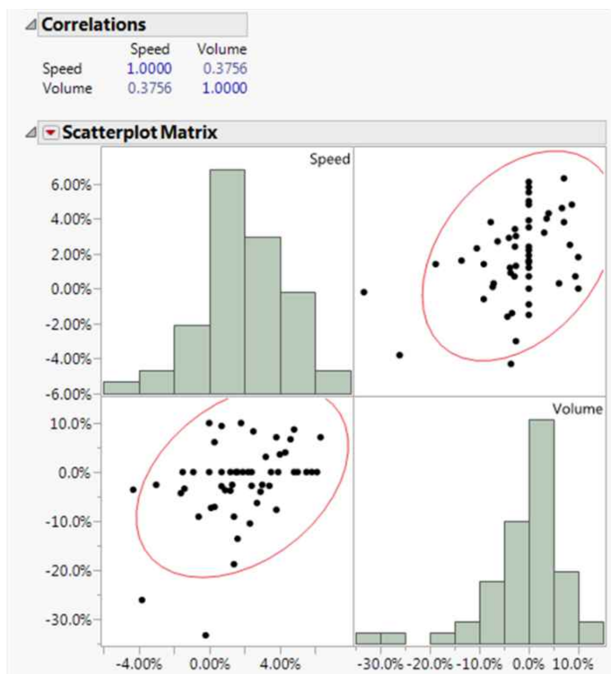


Figure 59: Correlation Analysis: Speed and Volume Errors

Taking into consideration the discussion previously presented, the next step allows the inspection of trends and tendencies in the data, by creating a plot of ground truth data (x-axis) versus VDS data (y-axis).This is referred to as calibration curve (see Figure 60) This analysis has the potential to generate insight on performance fluctuations at a system level. Each point in the plot represents a pair VDS-Ground Truth per lane, under a certain aggregation level at multiple locations.

In this type of plot, a perfect system would have every point located at the identity equation, where $x = y$. Given that Specification 660 (*9*) establishes a ±5% acceptable performance error for volume and a ±10% acceptable performance error for speeds, points falling within this range are considered to be compliant with the requirements.

In the plot, the continuous line in gray color indicates the identity equation, where $x = y$, and dashed lines indicate the acceptable performance error. In addition to that, a linear fit model was created, including a regression equation, providing the experimental relationship between the two data sources.

In Figure 60, adopting a 5-minute aggregation level, the described scatter plots are presented. The top part presents all points color-coded by station and shape-coded by lane. Based on the level of the coefficient of determination it can be observed that there is a strong correlation between the VDS and the ground truth data. Analyzing all detectors combined, the relationship found was $R^2 = 0.9983$. The intercept of the linear approximation indicates that it is expected that the ground truth will be, in average, off by 0.0137 vehicles, independently of the amount of vehicles traveling in the segment (statistically non-significant). The remaining term shows a factor of 1.013 accompanying the x-variable (VDS vehicle counts). This shows a slight tendency of undercounts done by the detectors. From this equation, it is expected that, given the ground truth data (y-variable) the expected VDS reading could be obtained (x-variable), and vice-versa. The bottom part of Figure 60 presents the same analysis, but for each detector separately. The linear regression for each detector resulted in a very similar outcome to the station study.

Out of the 60 pairs of VDS-Ground Truth data points, 11 are not within specification, representing 18.3% of the total points. Out of these 11 points, eight are undercounts and another three are overcounts. Detectors 146SB and 140NB are responsible for 10 of these errors, five errors each. All errors originated at detector 146SB are undercounts. By taking a closer look at those, it was possible to explain three of the errors by an interval skipped in SunGuide. Detector 140NB presented three undercounts and two overcounts.

The analysis also revealed a tendency in higher error magnitudes for undercounts and smaller error magnitudes for overcounts.

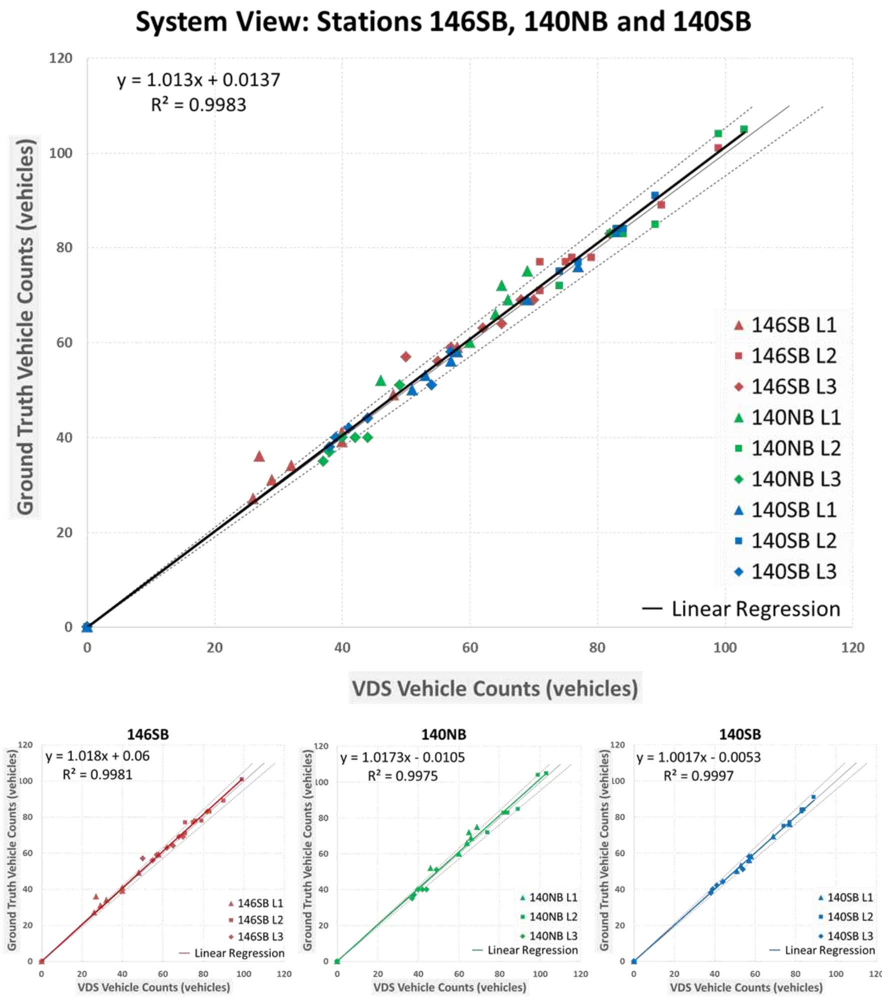


Figure 60: System View: Volume Errors (5-Minute Aggregation)

5.2.3 Causes of Volume Accuracy Error

Taking into consideration the findings from the previous sections, it was found that it was necessary to take a closer look, in the event level within each interval, to determine the causes of overcounts and undercounts within the aggregated intervals. Three main effects are discussed here: Interval synchronization, lane changing and occlusion. The next sections discuss each one of these effects and how each one of them could possibly affect VDS accuracy. In the sequence the theoretical discussion is applied to the Vero Beach data set.

5.2.3.1 Interval Synchronization

The traffic sensor system requires that all MVDSs respond to a polling request from the transportation management center. The system sends a request for data to the VDS at defined time steps (polling cycle). The VDS responds to this polling request by sending data from the most recently completed interval. The duration of polling cycles varies by district but typical values are 20 and 60 seconds.

The detector stores the data element from each completed interval in its internal memory. The internal memory generally holds an ordered list in the form of a stack. The stack has a Last-In-First-Out (LIFO) queuing policy, meaning that the most recent data element is located at the first position in the list and is also the first to be retrieved. It also follows that once the capacity of the memory is full, the last element (oldest data) is eliminated and the most recent is added to the beginning of the list.

Once a time interval is completed, the associated data element is placed at the top of that stack and is considered as the most recent data element. As part of the data retrieval process, the Traffic Sensor Subsystem (TSS) main subsystem sends a request for the most recent interval of data. The interval located at the first position of the stack of all completed intervals is then sent to the requesting object. This process is repeated for every polling cycle. The retrieved data are time stamped using SunGuide which takes place after the polling cycle is completed. Therefore, there is a systematic delay of one polling cycle between the actual time of the detector count in the field and the timestamp of the retrieved data. Polling cycle offset can cause systematic effects such as double counting or interval skipping, as explained in the following section.

In the scenario where all detectors and system clocks are synchronized, data can be polled either with a shorter or longer period than the interval's fixed period. This means that polling is either more frequent or less frequent than the interval period on the detector's ends. This difference in polling frequency can occur for a number of reasons, such as server or network communication delay, configuration changes or software issues. This can also occur on the VDS' end due to software configuration changes.

Figure 61 shows an example of the effect of the difference in polling cycle intervals between the detector and the data retrieval system. The polling cycle offset factor multiplies the intended system polling cycle to reflect polling cycle offset on the data retrieval system. A polling cycle offset factor of 1.1 means that the polling cycle duration for the data retrieval system is 10 percent greater than VDS data collection interval. In this case, the retrieval system has a less frequent polling cycle (slower polling rate) and some VDS intervals are skipped (see the top part of Figure 61). Interval skipping happens because the VDS interval time has already passed when the detector receives the request for data, and a new interval has already been placed on top of the stack as the most recent. Interval skipping causes the system to retrieve the next interval of data to be processed and timestamped. The bottom part of Figure 61 presents an example of double. This effect occurs when the polling cycle duration of the retrieval system is shorter than the data collection interval of the VDS.

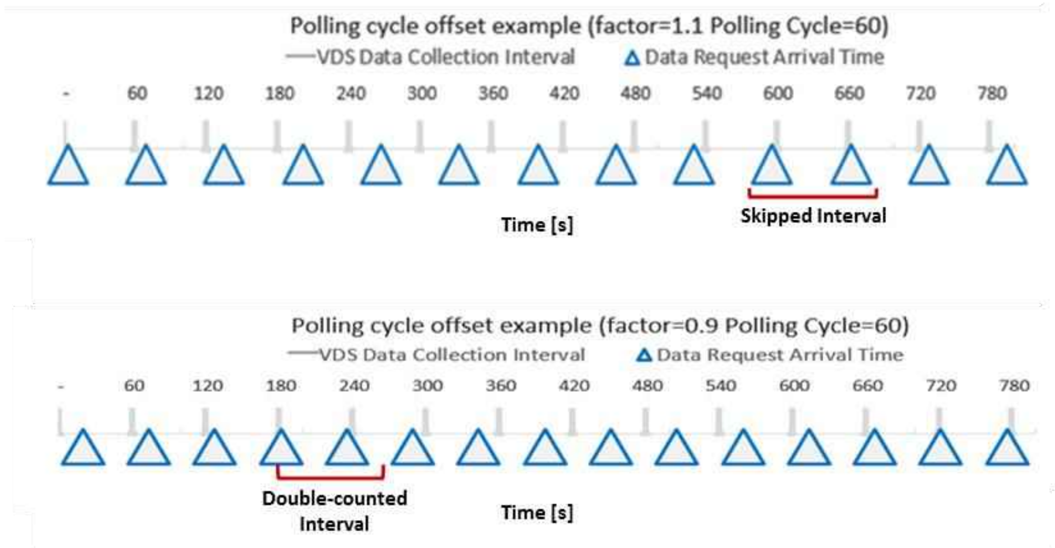


Figure 61: Examples of Polling Cycle Offset Error

Interval skipping and overcounting are proportional to the polling cycle offset. A polling cycle five percent less than the intended value will tend to skip the same percentage of intervals. The same applies to the overcounting side of the graph. Since the estimate of interval skipping and overcounting is a deterministic calculation, results may vary randomly in reality depending on the traffic variable of interest and the number of vehicles in the skipped or double counted interval. For volume, polling offset will have noticeable results because volume is accumulated over time. For speed, the effect of polling time offset is averaged overtime therefore double counting or skipping will not severely affect the measurement.

1.1.1.1 Lane Changing

Due to the nature of the process of establishing the ground truth data, some errors that might be attributed to the VDS could end up not being incorrect detections. During the video reduction, the protocol adopted defines that the vehicle should be assigned to the lane where most of its body is located, when its position is centered in the screen. This process is not automated and there is no direct measurement of the position of the vehicle. For some events this definition is very subjective. Another reason that could potentially lead to discrepancies between the VDS data and the ground truth data are the relative alignment between the traffic camera and the sensor. If this is the case, the decision would be made at different points for each source of data, which could potentially justify discrepancies. Since one has no control over this situation, it was decided that this aspect should be considered as one potential cause of error, deserving an assessment in an individual category.

1.1.1.2 Occlusion

Traffic monitoring using over-roadway sensors is usually done in one of two ways. The mounting location could be either over the lane of traffic or on the side of the roadway. In the first case, the detectors are placed over the lane of traffic they are intended to monitor, so the view cannot be occluded by other passing vehicles. One major disadvantage in this type of detector mounting is the need to disrupt the flow of traffic for installation, calibration or maintenance, since in most cases bucket trucks are necessary to access the sensor, requiring lane closure.

Detectors mounted on the side of the road do not disrupt traffic during installation or calibration processes, making them the most common choice. For those cases, to obtain optimized performance, the mounting location must generate an unobstructed view of the lanes, since the detector is setup to view multiple lanes of traffic. According to the FHWA Traffic Detector Handbook (*6*), detectors mounted on the side of a roadway may experience two types of data anomalies. The first and most common occurs when tall vehicles are passing in the detection zone and therefore blocking the sensor view of distant lanes. This occlusion may cause an undercount if a vehicle is traveling in the occluded area. The consequences are errors being introduced in the volume measurement, due to undercounting and also may generate a false average speed measurement. The other anomaly occurs when the sensor is susceptible to misinterpreting tall vehicles by projecting the detection in adjacent lanes. Also caused by tall vehicles, this anomaly will have the opposite effect as the previous one, inducing overcounts and possibly reporting a false average speed. Figure 62 illustrates the side-fire detector mount and the possible anomaly effects.

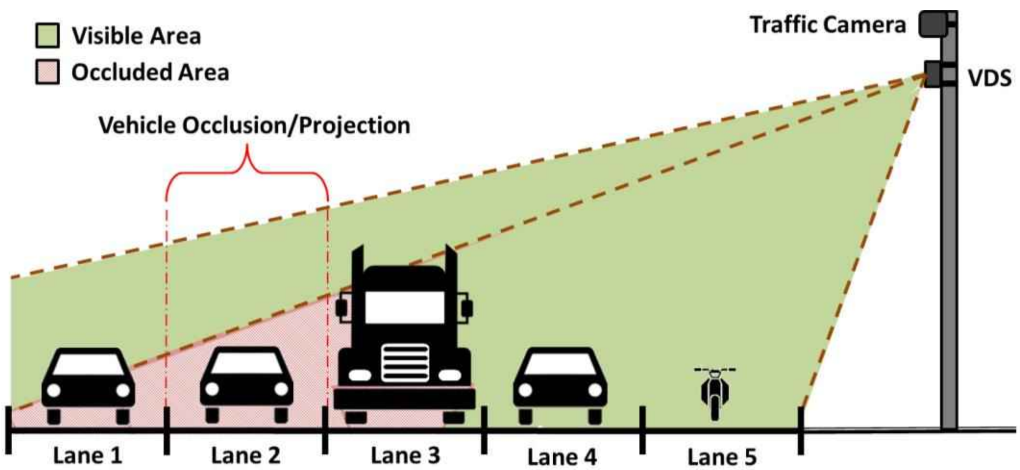


Figure 62: Occlusion and Projection Anomalies

Some sensors may be more prone to these errors than others, so sensor type must be analyzed depending on the needs of each application. Mounting height, distances the closest and further away lanes, road configuration and sensor angles must also be considered. One other relevant aspect to be considered is the vehicle mix in the road. As mentioned, this type of error occurs in the presence of tall vehicles that may possibly occlude other vehicles or project a false reading in an adjacent lane.

The following images present possible scenarios where these anomalies could take place. It is important to notice that the traffic cameras are, in the majority of the time, installed above the

VDS. This is true for all cameras in the studied segment, so the vehicles partially visible in the figures below should be even more occluded from the VDS angle. Figure 63 presents scenarios where occlusion is very likely to occur. In Figure 63(a) and Figure 63(c) the VDS may undercount for the middle lane. In Figure 63(b) the VDS may undercount for the top lane in the video. Figure 64 presents scenarios where occlusion is also possible to occur, but less likely than the previous cases. Figure 64(a) indicates a possible occlusion on the top lane, two lanes away from the tall vehicle. Figure 64(b) shows a medium vehicle possibly occluding a small vehicle. Figure 64(c) show cases where even small trucks could be occluded.

(a) (b) (c)

Figure 63: Anomaly Types: Very Likely Occlusion Scenario

(a) (b) (c)

Figure 64: Anomaly Types: Possible Occlusion Scenarios

Figure 65 shows cases where tall vehicles may be projected in adjacent lanes generating overcounts. Figure 65(a) could possibly generate overcount in the middle lane, while Figure 65(b) and Figure 65(c) could generate overcount in the top lane.

(a) (b) (c)

Figure 65: Anomaly Types: Possible Projection Scenarios

5.2.4 Causes of Error for the I-95 Vero Beach Data Set

Each data set was analyzed in detail. A tool was created in Excel, whose objective was to gain insight in the way each one of the factors may occur, linking each individual cause of error to the effect on the interval. In order to do so, the video was paused when each vehicle is on the detection zone and each frame was analyzed given the context of the accuracy error present in each interval.

Figure 66 shows an example of the spreadsheet created for the purpose of this analysis. Excel columns from B through I retrieve from the SunGuide data all vehicle length data for the detected vehicles, reporting the classification bins. Excel columns from “K” to “N” have the time interval data and columns from “O” through “W” retrieve both Ground Truth and SunGuide vehicle counts, calculating the error and indicating the errors using a color scale for easy visualization. At the leftmost part of Figure 66 it is possible to notice that several rows are grouped and collapsed (indicated by the sign positive). By clicking the positive sign the rows are expanded, showing each event in detail, including a screenshot of the vehicle in the detection zone.

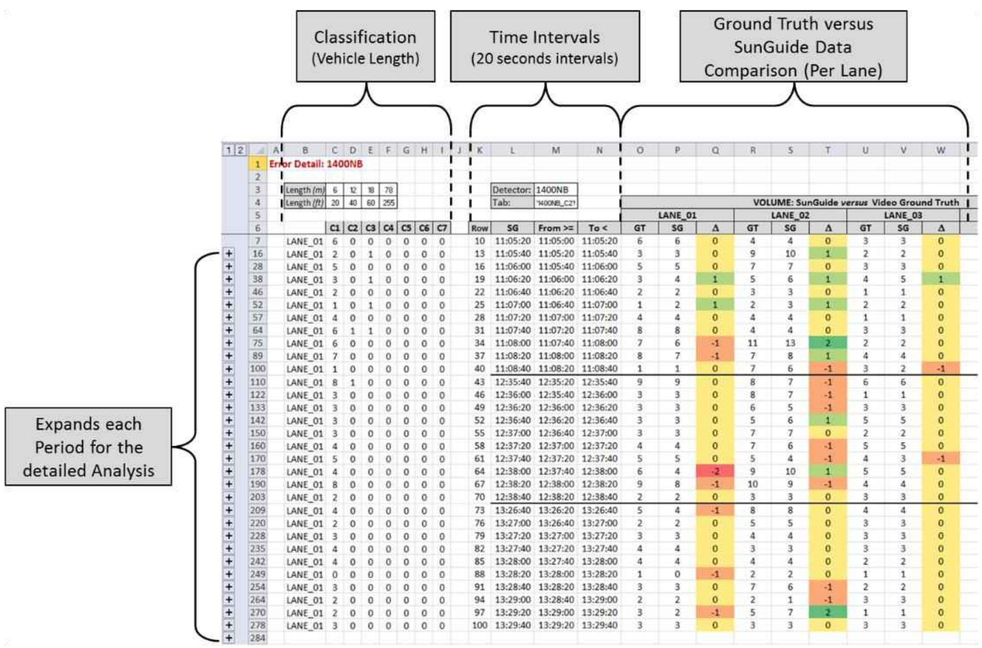


Figure 66: Tool Example: Error Detail Analysis (Collapsed)

Figure 67 shows the appearance of the tool when the rows are expanded, exhibiting the screenshots of each detection. Inside the shape indicated as “A” are the vehicles classified within length bins for each one of the lanes. This information aids the screenshot analysis process by helping to identify the errors in each period. Inside the shape indicated as “B” are the volumes for each lane within each period. In box “C” are screenshots with each vehicle considered in the ground truth data. Box “D” contains the timestamps for each one of the screenshots.

In any case, the source of error was suspect, the screenshot is marked with red borders and an error code index is attributed. In the image, it is possible to see the error code 302, indicating a possible occlusion.

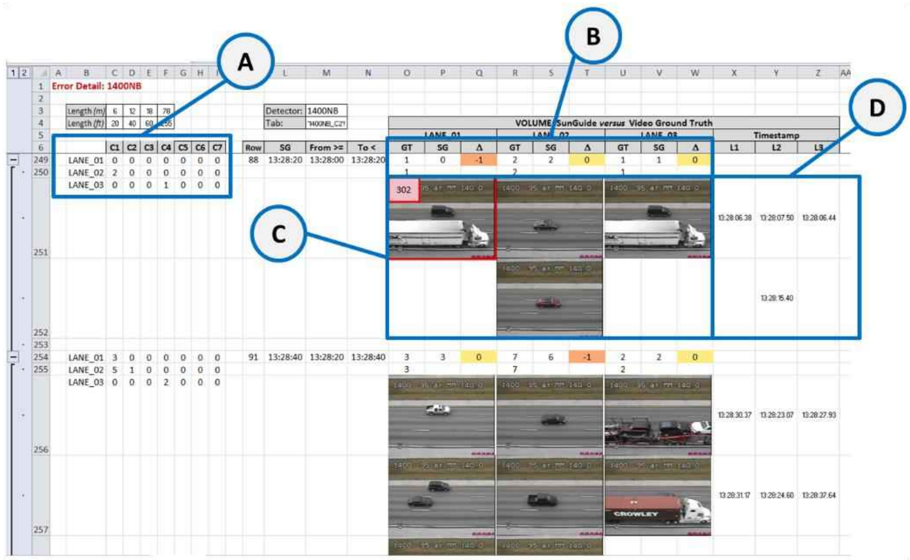


Figure 67: Tool Example: Error Detail Analysis (Expanded)

5.2.4.1 140NB Detector

This section covers the errors found using the spreadsheet and its effects on the VDS accuracy for each interval. The analysis include occlusion errors, interval synchronization errors, and errors due to lane changing. Three data sets from different intervals were analyzed for this detector:

- Interval 1: from 11:05:00 to 11:08:40,
- Interval 2: from 12:35:20 to 12:38:40,
- Interval 3: from 13:26:20 to 13:29:40.

The detailed analysis using the Excel tool revealed a total absolute error of 32 vehicle counts for the three lanes of traffic. Among those, 19 were undercounts and 13 were overcounts.

5.2.4.1.1 Estimation of Occlusion Errors

Tall vehicles are a well-known factor responsible for occlusion and projection errors in vehicle counts. Given the camera position and the lane numbering scheme, the adopted assumption of possible occlusion scenarios are:

- Lane 1, the furthest lane from the VDS/Camera, is subject to a high chance of occlusion from tall vehicles traveling on lane 2 and a low chance of occlusion from tall vehicles traveling on lane 3.

- Lane 2, the middle lane, is only subject to occlusion caused by tall vehicle traveling on lane 3.
- Lane 3, the closest lane to the VDS/Camera, is not subject to occlusion.

Considering only the lanes that can be possibly occluded, the analysis revealed a total absolute error of 29 vehicle counts, among which 17 were undercounts and 12 were overcounts. The analysis also revealed that, out of the 17 undercounts, 10 could be explained by occlusions in lanes 1 and 2. Table 19 shows the summary of the findings.

Table 19: 140NB: Summary of Occlusion Errors

Interval	Lane	Volume Error			Occlusion Events	Percent Contribution	
		Over	Under	|Δ|		Under	Total Error
1	1	2	2	4	1	50.0%	25.0%
	2	6	1	7	0	0.0%	0.0%
2	1	0	3	3	2	66.7%	66.7%
	2	2	6	8	4	66.7%	50.0%
3	1	0	3	3	2	66.7%	66.7%
	2	2	2	4	1	50.0%	25.0%
Acc.	1	2	8	10	5	62.5%	50.0%
	2	10	9	19	5	55.6%	26.3%
	Station	12	17	29	10	58.8%	34.5%

Table 19 also reveals that 50% of the total error in lane 1 can be explained by occlusions, while in lane 2 the occlusions explain over 26% of the error. The undercounting errors are explained by occlusion in 62.5% of the cases in lane 1 and 55.6% of the cases in lane 2. Figure 68 and Figure 69 show the detail of each one of the ten cases considered as occlusion. Aggregating lanes 1 and 2, 34.5% of the absolute errors are explained by occlusion (58.8% of the undercounts).

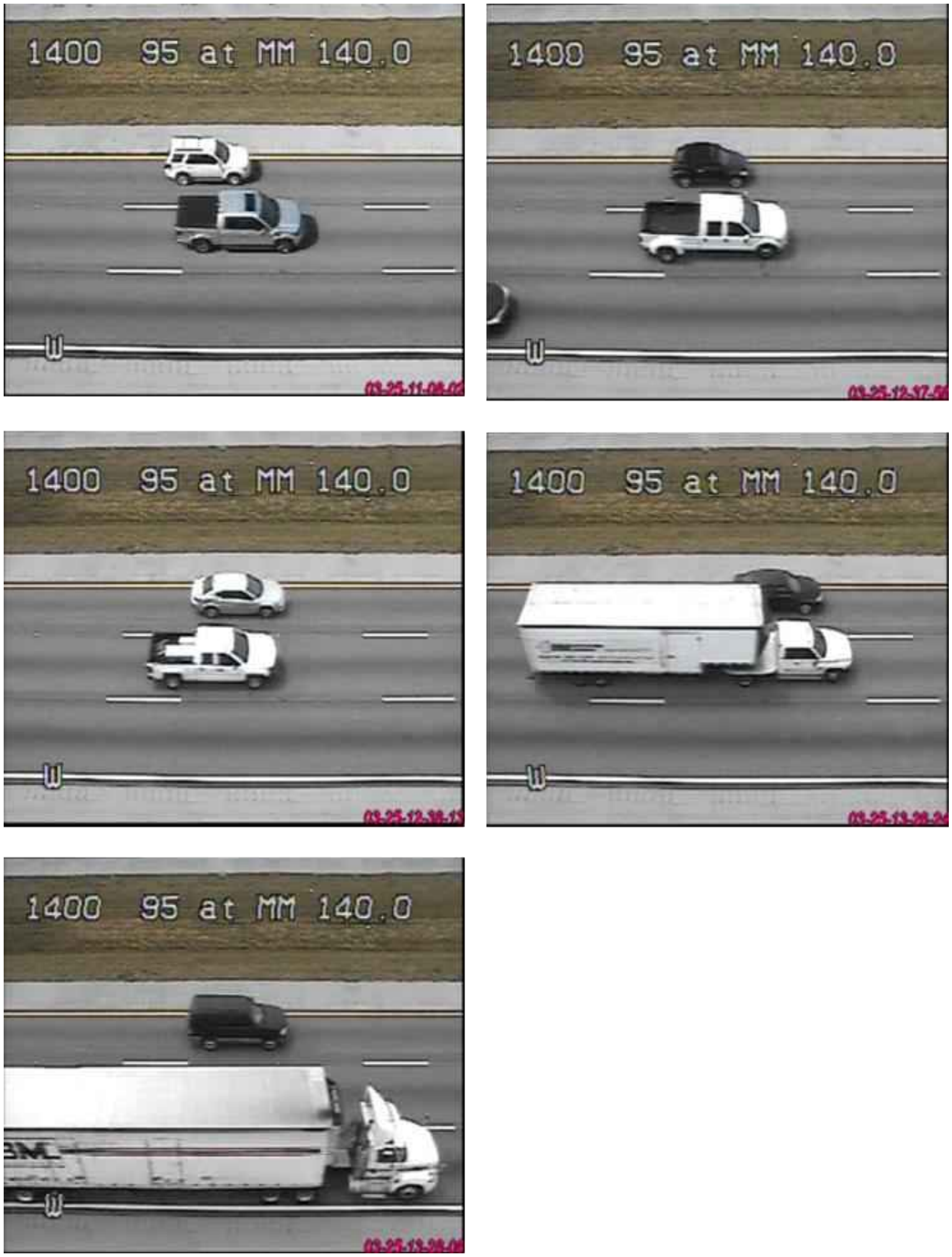


Figure 68: 140NB: Lane 1 Occlusion Cases

Figure 69: 140NB: Lane 2 Occlusion Cases

It is expected that the occlusions will be directly related to the occurrence of high profile vehicles traveling in both lanes 2 and 3. Since the height of the vehicles is not available, the assumption that long vehicles will also be tall is adopted. Table 20 summarizes the vehicle composition where C1 to C4 indicate the length bin categories to classify vehicle lengths, where C1 ranges from 0 ft. to 20 ft., C2 ranges 20 ft. to 40 ft., C3 ranges from 40 ft. to 60 ft., and C4 is above 60 ft.

Table 20 – 140NB: Vehicle Composition

Interval	Lane	Number of Vehicles C1	C2	C3	C4	Percent Vehicle Composition C1	C2	C3	C4
1	1	43	1	4	0	89.6%	2.1%	8.3%	0.0%
	2	52	9	0	5	78.8%	13.6%	0.0%	7.6%
	3	15	4	3	6	53.6%	14.3%	10.7%	21.4%
	Station	11	14	7	11	77.5%	9.9%	4.9%	7.7%
2	1	43	1	0	0	97.7%	2.3%	0.0%	0.0%
	2	55	7	0	1	87.3%	11.1%	0.0%	1.6%
	3	23	5	2	7	62.2%	13.5%	5.4%	18.9%
	Station	12	13	2	8	84.0%	9.0%	1.4%	5.6%
3	1	27	0	0	0	100.0	0.0%	0.0%	0.0%
	2	35	5	0	2	83.3%	11.9%	0.0%	4.8%
	3	11	3	2	9	44.0%	12.0%	8.0%	36.0%
	Station	73	8	2	11	77.7%	8.5%	2.1%	11.7%
Acc.	1	11	2	4	0	95.0%	1.7%	3.4%	0.0%
	2	14	21	0	8	83.0%	12.3%	0.0%	4.7%
	3	49	12	7	22	54.4%	13.3%	7.8%	24.4%
	Station	30	35	11	30	80.0%	9.2%	2.9%	7.9%

It is noticeable that the majority of long trucks are traveling on lanes 2 and 3. In fact, 4.7% of the vehicles traveling in lane 2 are over 60 ft. In lane 3, this value is over 24%. Another 7.8% of the vehicles traveling in lane three are over 40 ft. Vehicles between 20 ft. and 40 ft. are also a potential source of occlusion and represent over 12% of the vehicles traveling in lane 2 and over 13% of the vehicles traveling in lane 3.

5.2.4.1.2 Estimation of Interval Synchronization Errors

As mentioned earlier in this section, the data pooling process can potentially cause two types of VDS accuracy issues. The first failure mode discussed may generate interval skipping or double-counting. The second possible failure mode may be induced when VDS data and ground truth data have different sources of timestamp. The VDS data are timestamped using SunGuide when the data are received from the detector. The method used to obtain ground truth in this study timestamps the data based on the recorded video from the traffic camera. In a previous section it was shown that we have enough evidence that both data sets are not out of sync for more than one second. Nevertheless it is not possible to determine exactly the offset within that one second time window. The detailed analysis showed no sign of double-counted or missed intervals but significant evidence was found to justify errors due to apparent misclassification within intervals, when comparing the ground truth method to the VDS data. Since these errors may be attributed to the method, it was decided that it shouldn't be attributed to the VDS itself, so the errors were treated separately in the same way that occlusion errors were treated. Table 21 summarizes the effect of the interval synchronization errors.

Table 21: 140NB: Summary of Interval Synchronization Errors

Interval	Lane	Volume Error			Interval Sync. Errors	Percent Contribution of Interval Sync. Errors compared to
		Over	Under	5.2.4.1.		
1	1	2	2	4	0	0.0%
	2	6	1	7	2	28.6%
	3	1	1	2	0	0.0%
2	1	0	3	3	0	0.0%
	2	2	6	8	2	25.0%
	3	0	1	1	1	100.0%
3	1	0	3	3	0	0.0%
	2	2	2	4	0	0.0%
	3	0	0	0	0	-
Acc.	1	2	8	10	0	0.0%
	2	10	9	19	4	21.1%
	3	1	2	3	1	33.3%
	Station	-	-	32	5	15.6%

5.2.4.1.4 Estimation of Lane Changing Errors

Lane Changing Errors, are caused by different interpretation of vehicles changing lanes within the detection zone. This type of error also shouldn't be directly attributed as inaccuracy of the VDS since it is not possible to precisely determine in the video the portions of the vehicle in each lane. Deciding in which lane the vehicle is during the ground truth data reduction is subjective and uses a different method as the one used by the VDS. This aspect of the ground truth data are determined visually, while the VDS uses the measured range and previous lane configuration to allocate the vehicles in each lane. Table 22 summarizes the errors that could be attributed to vehicles changing lanes within the detection zone.

Table 22: 140NB: Summary of Lane Changing Errors

Interval	Lane	Volume Error			Lane Changin	Percent Contribution of Lane Changing Errors
		Over	Under	|Δ|		
1	1	2	2	4	0	0.0%
	2	6	1	7	0	0.0%
	3	1	1	2	0	0.0%
2	1	0	3	3	1	33.3%
	2	2	6	8	1	12.5%
	3	0	1	1	0	0.0%
3	1	0	3	3	1	33.3%
	2	2	2	4	1	25.0%
	3	0	0	0	0	-
Acc.	1	2	8	10	2	20.0%
	2	10	9	19	2	10.5%
	3	1	2	3	0	0.0%
	Station	-	-	32	4	12.5%

5.2.4.1.5 Other Errors Attributed to the VDS

Taking into consideration the three types of error previously discussed, this section summarizes the errors that may be attributed to the VDS. Table 23 shows the data for each lane within each interval. As we can see, for lane 1, three out of 10 errors (30.0%) are attributed to the VDS. For lane 2, eight out of 19 errors (42.1%) are attributed to the VDS. For lane 3, two out three errors (66.7%) are attributed to the VDS. Considering the three lanes combined, 40.6% of the error is attributed to the VDS.

Table 23: 140NB: Summary of Errors Attributed to the VDS

Interval	Lane	ABS Error |Δ|	Error Types			Other Errors due to VDS	Percent Contribution of Other Errors in Total Error
			Occlusion	Lane Changes	Interval Sync.		
1	1	4	1	0	0	3	75.0%
	2	7	0	0	2	5	71.4%
	3	2	0	0	0	2	100.0%
2	1	3	2	1	0	0	0.0%
	2	8	4	1	2	1	12.5%
	3	1	0	0	1	0	0.0%
3	1	3	2	1	0	0	0.0%
	2	4	1	1	0	2	50.0%
	3	0	0	0	0	0	-
Acc.	1	10	5	2	0	3	30.0%
	2	19	5	2	4	8	42.1%
	3	3	0	0	1	2	66.7%
	Station	32	-	-	-	13	40.6%

5.2.4.2 140SB Detector

This section covers the errors found using the spreadsheet and its effects on the VDS accuracy for each interval. First the occlusion errors are discussed, then in the sequence the errors due to interval synchronization and at last errors due to lane changing effect. Three data sets from different intervals were analyzed for this detector:

- Interval 1: from 12:18:40 to 12:24:20,
- Interval 2: from 13:10:00 to 13:15:20,

The detailed analysis using the Excel tool revealed a total absolute error of 15 vehicle counts, among which five were undercounts and 10 were overcounts.

5.2.4.2.1 Estimation of Occlusion Errors

The analysis of 11 minutes of traffic revealed five undercounts for this VDS. The detailed study didn't provide any evidence that these undercounts could be justified by occlusion. Two reasons were considered to explain why the detailed analysis didn't encounter any case occlusions.

The first reason is due to the lane position in relation to the VDS. As presented on Figure 53 (and reproduced here on Figure 70), the northbound section is very close to the VDS and traffic camera, while the southbound section is far away, affecting the angle in which the road is seeing.

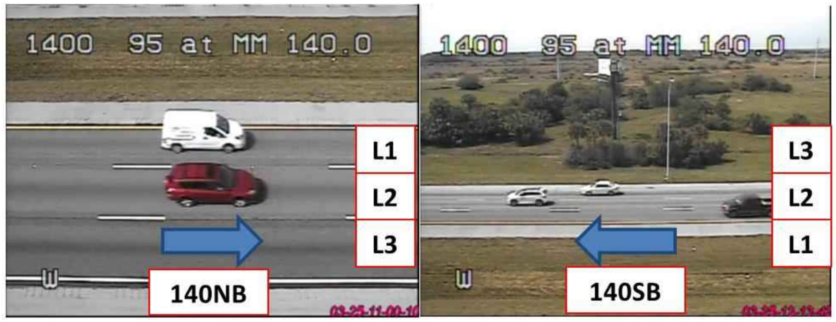


Figure 70 : 140NBSB: Angle of View Comparison

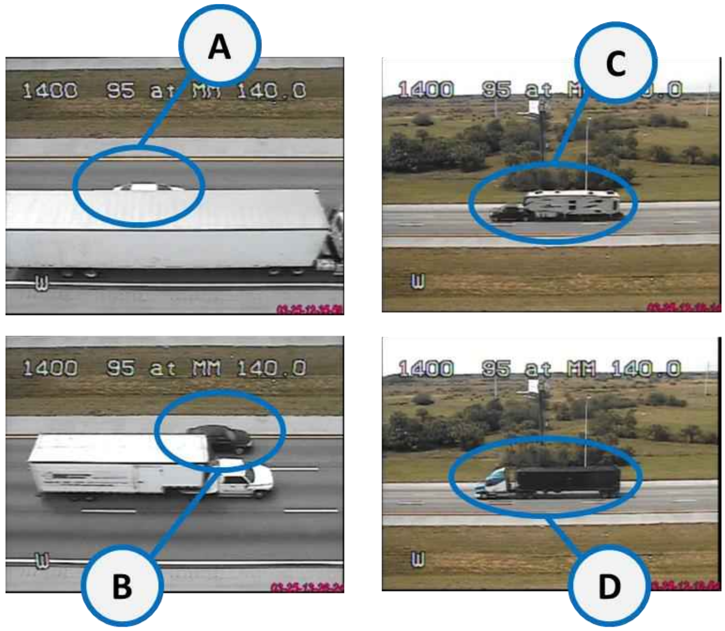
For the northbound section the slower lanes (higher flow of tall vehicles), were closer to the VDS. The fastest lane (higher flow of small vehicles) is more likely to be occluded given the situation. For the southbound section the fastest lane is closer to the VDS, so it can't be occluded. During the 11 minutes of analyzed video no tall vehicles were found traveling in the fastest lane. Given this scenario, the possibility for occlusion is severely reduced.

The second explanation is related to the process of obtaining the ground truth data. Given the angle of view for the southbound section, it is expected that less occurrences of occlusion can be identified, given our method of analysis. In that sense, for the northbound section it is expected that the video recorded from the traffic camera will include at least a section of the top part of occluded vehicles, as shown in Figure 70 and Figure 71. The visual information will allow the attaining of more reliable ground truth data for volumes. One important factor to keep in mind is that the traffic camera is always installed in a higher position than the VDS.

For the northbound section, this configuration will result in a complete vehicle occlusion from the VDS angle of view, while the traffic camera higher position still shows the top part of the occluded vehicles. On the other hand, for the southbound section it is expected that the difference in height between the VDS and the traffic camera will have no effect and it won't be possible to detect the occlusion.

Figure 71 (a) shows two examples of occlusion where it is possible to see the top part of the vehicle, allowing it to be considered in the ground truth data. The first screenshot (indicated by "A") shows an occlusion on lane 2. The second screenshot (indicated by "B") shows an occlusion on lane 1.

Figure 71 (b) shows two examples of tall vehicles for the southbound section. Both vehicles (indicated by "C" and "D") are traveling in the center lane that can potentially occlude lane 3. Any eventual occlusion happening on lane three could not be detected using the traffic camera video.



(a) **(b)**

Figure 71 – Detection View: Effect on Occlusion

5.2.4.2.2 Estimation of Interval Synchronization Errors

The detailed analysis showed no sign of double-counted or missed intervals but significant evidence was found to justify errors due to apparent misclassification within intervals, when comparing the ground truth method to the MVDS data.

Since these errors may be attributed to the method, it was decided that it shouldn't be attributed to the MVDS itself, so the errors were treated separately in the same way that occlusion errors were treated. Table 24 summarizes the effect of the interval synchronization errors.

Table 24: 140SB: Summary of Interval Synchronization Errors

Interval	Lane	Volume Error			Interval Sync. Errors	Percent Contribution of Interval Sync. Errors compared to Total Error
		Over	Under	|Δ|		
1	1	2	1	3	2	66.7%
	2	2	2	4	2	50.0%
	3	3	0	3	0	0.0%
2	1	3	1	4	2	50.0%
	2	1	1	2	0	0.0%
	3	0	0	0	0	-
Acc.	1	5	2	7	4	57.1%
	2	3	3	6	2	33.3%
	3	3	0	3	0	0.0%
	Station	-	-	16	6	37.5%

5.2.4.2.3 Estimation of Lane Changing Errors

Lane Changing Errors, are caused by different interpretation of vehicles changing lanes within the detection zone. This type of error also shouldn't be directly attributed as inaccuracy of the MVDS since it is not possible to precisely determine in the video the portions of the vehicle in each lane.

Deciding which lane the vehicle is in during the ground truth data reduction is subjective and uses a different method as the one used by the VDS. This aspect of the ground truth data are determined visually, while the MVDS uses the measured range and previous lane configuration to allocate the vehicles in each lane. Table 25 summarizes the errors that could be attributed to vehicles changing lanes within the detection zone.

Table 25: 140SB: Summary of Lane Changing Errors

Interval	Lane	Volume Error			Lane Changing Errors	Percent Contribution of Lane Changing Errors compared to Total Error
		Over	Under	|Δ|		
1	1	2	1	3	1	33.3%
	2	2	2	4	1	25.0%
	3	3	0	3	0	0.0%
2	1	3	1	4	1	25.0%
	2	1	1	2	1	50.0%
	3	0	0	0	0	-
Acc.	1	5	2	7	2	28.6%
	2	3	3	6	2	33.3%
	3	3	0	3	0	0.0%
	Station	-	-	16	4	25.0%

5.2.4.2.4 Other Errors Attributed to the MVDSs

Taking into consideration the three types of error previously discussed, this section summarizes the errors that may be attributed to the MVDS. Table 26 shows the data for each lane within each interval. As we can see, for lane 1, one out of seven errors (14.3%) are attributed to the VDS. For lane 2, two out of six errors (33.3%) are attributed to the MVDS. For lane 3, all three errors (100.0%) are attributed to the MVDS. Considering the three lanes combined, 37.5% of the error is attributed to the MVDS.

Table 26: 140SB: Summary of Errors Attributed to the VDS

Int.	Lane	ABS Error |Δ|	Error Types			Other Errors due to VDS	Percent Contribution of Other Errors in Total Error
			Occlusion	Lane Changes	Interval Sync.		
1	1	3	0	1	2	0	0.0%
	2	4	0	1	2	1	25.0%
	3	3	0	0	0	3	100.0%
2	1	4	0	1	2	1	25.0%
	2	2	0	1	0	1	50.0%
	3	0	0	0	0	0	-
Acc.	1	7	0	2	4	1	14.3%
	2	6	0	2	2	2	33.3%
	3	3	0	0	0	3	100.0%
	Station	16	-	-	-	6	37.5%

5.3 I-275 Saint Petersburg, FL, Testbed Data Set

FDOT District 7 (Tampa-Saint Petersburg) implemented a MVDS testbed in the southbound direction of the I-275 corridor between mile markers 27 and 31. The testbed was implemented for a long-term evaluation study of several VDS, to assess volume, occupancy, and speed accuracy by lane.

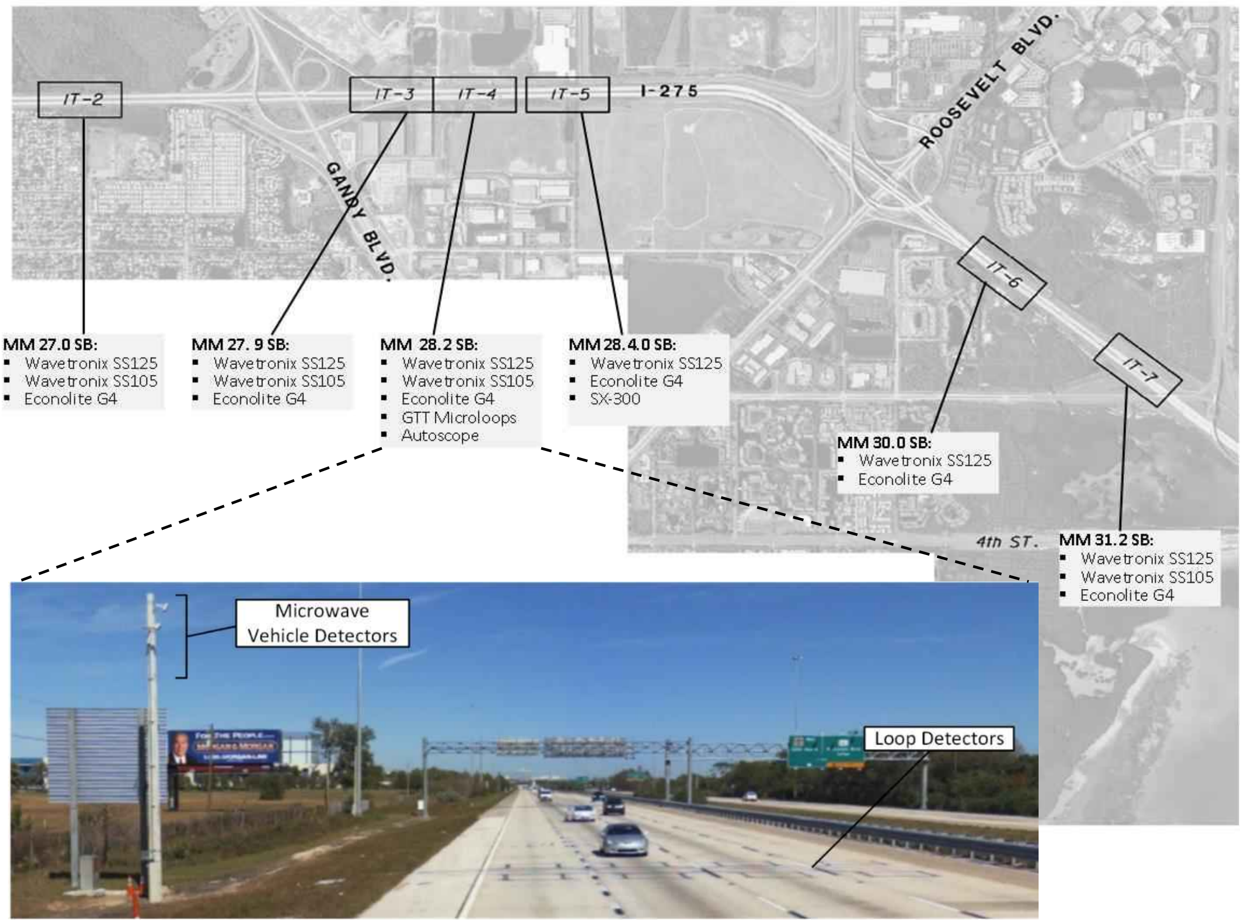


Figure 72: Example of Detector Setup in District 7 Testbed

5.3.1 Data Analysis

Data from the D-7 testbed in flat file format was mined for years 2014 through 2016.The processed data were indexed and stored in a SQL Server Express Database®. Data processing was performed using the Python language.

5.3.2 VDS Synchronization

MVDS data are retrieved and time-stamped according to system's time on each polling cycle. The initial assumption was that all VDS data were on the same time reference. Under this assumption, accuracy calculations for volume and speed were found systematically low. An iterative search procedure was applied between ground truth detectors and test MVDS to correct time synchronization effects. Timestamps were shifted based on a time lag expressed as an integer multiple of the polling cycle. The polling cycle was considered the maximum level of resolution that can be achieved by the data collection system (no interpolation within the polling cycle). A lag of -4 polling cycles means that the MVDS timestamp needs to be shifted 4 polling cycles back in time in order to align with the ground truth detector (in this case ground truth is delayed 4 polling cycles).

The objective used for the synchronization analysis was to minimize relative percentage error (min=0) which is equivalent to maximizing accuracy (max=100). In the case of the D7-testbed, the polling cycle was 60 seconds. Figure 73 presents an example of the initial screening analysis for a randomly selected day in 2014. It can be observed that at shorter aggregation intervals, the effect of time synchronization is more noticeable. For 5-min aggregation time synchronization improved 12 percentage points in accuracy with respect to the original data set. This constituted an improvement of from 75% at 0 lag up to an 87% at -4 lag. For 15 minute the effect of the lag reduced accuracy about three percentage points. When the aggregation interval is one hour the change is less noticeable. In general, aggregation intervals close to the polling cycle length tend to be more affected by time synchronization. For example, using data in 5-min interval with a polling cycle of 20 seconds may be more robust to time offsets than using one min polling cycle. It also has more resolution to synchronize data for off-line applications. Synchronization was applied on a per-day basis to all the VDS data.

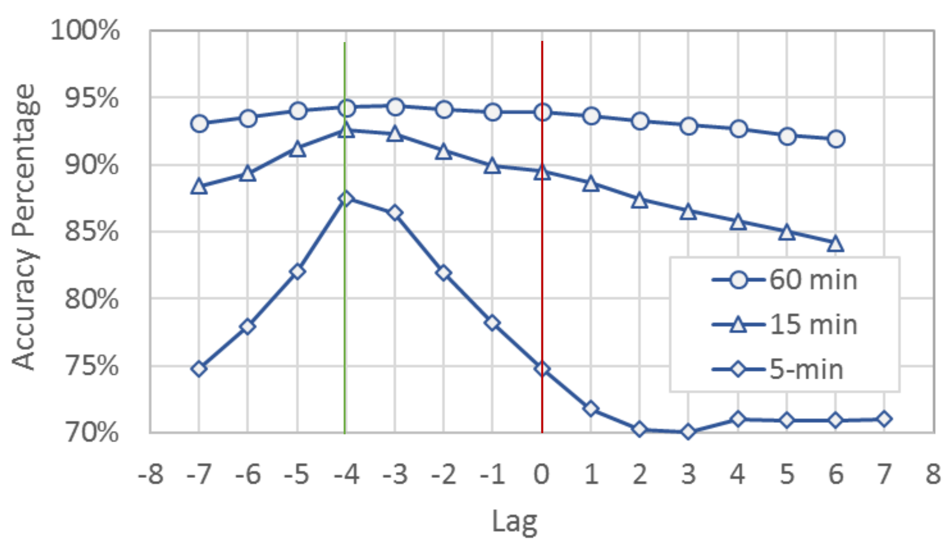


Figure 73: Effect of Lag in Volume Accuracy

Figure 74 presents the effect of time lag in speed accuracy by time interval. It can be observed that speed accuracy is not sensitive to time lags. Individual speeds fluctuate around the characteristic speed of the roadway segment (mean speed) at the prevailing conditions (e.g., free flow speed for LOS A, B, C, etc.). When averaged over an interval, it will tend to converge to that mean characteristic value. Unless the prevailing conditions change drastically in an interval with duration less than the time lag, there will be no noticeable effect on speed accuracy. This is consistent with some of the issues experienced by the interviewed districts.

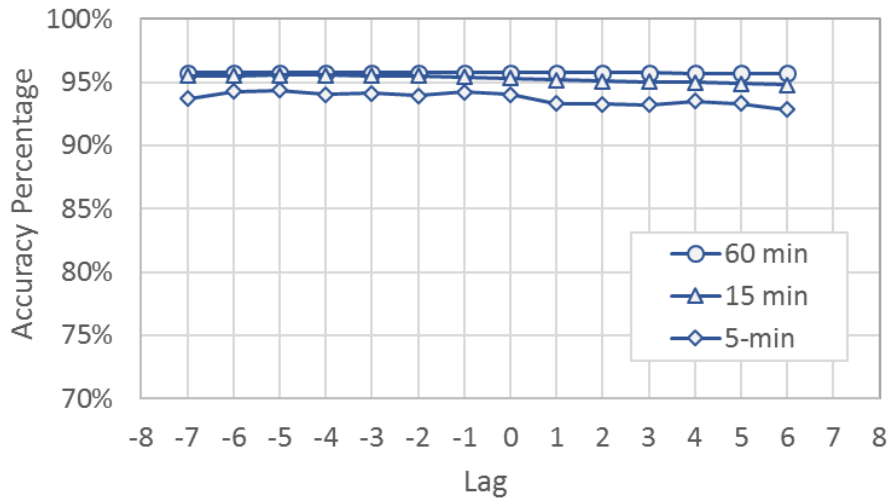


Figure 74: Effect of Lag in Speed Accuracy

5.3.2.1 Effects on TMC applications

Figure 75 presents the lags between co-located loop detectors and MVDS. The ground truth was chosen as loop detectors. The time lags were calculated with respect to the ground truth detector. The selected MVDS are always with a negative lag from two to 4 polling cycles from the ground truth detector. This may be an indication that the MVDS and the ground truth are in subsystems with different time frames and one of them is experiencing data processing delays.

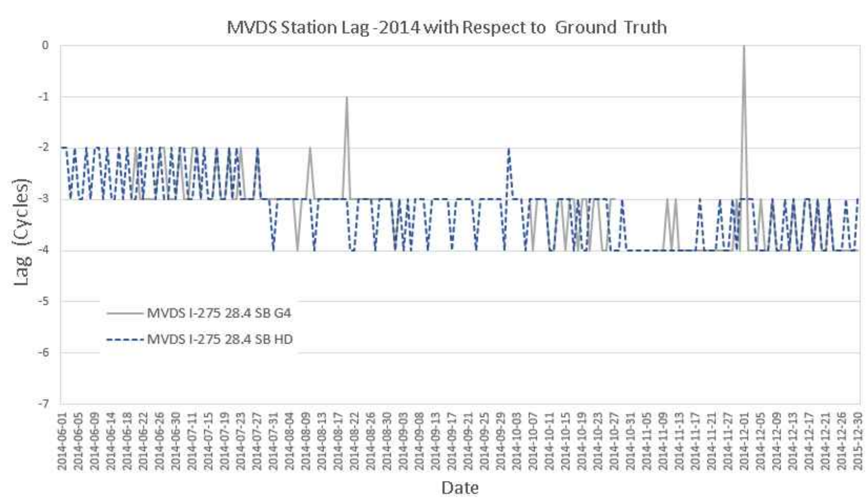


Figure 75: Lag Comparison on a Sample of Co-Located MVDS

Figure 76 presents a typical scenario of co-located MVDS short-term data discrepancies. If the VDS' are not synchronized, they could be at any random instant within their data collection interval. In Figure 76 it is assumed that an event of interest occurs at certain time t*. For VDS 1 the event occurred after the most recent data collection interval was completed and therefore it will not be contained in the reporting interval at tb. For VDS 2 the event of interest happened before completing the data collection interval. In this latter case, the event of interest is included and reported when the polling system obtains the interval data at tb. In VDS 1, the event of interest will be collected at the next polling cycle and reported in tc. These delays are random because the system polling cycle clock and the VDS clock may be at an arbitrary setting at any given time. The effect of synchronization may induce a delay in the time to detect an event of interest. From Figure 76 it can be observed that shorter polling cycles and periodic clock synchronization have the potential to improve the time to detect and overall data quality for short-term applications.

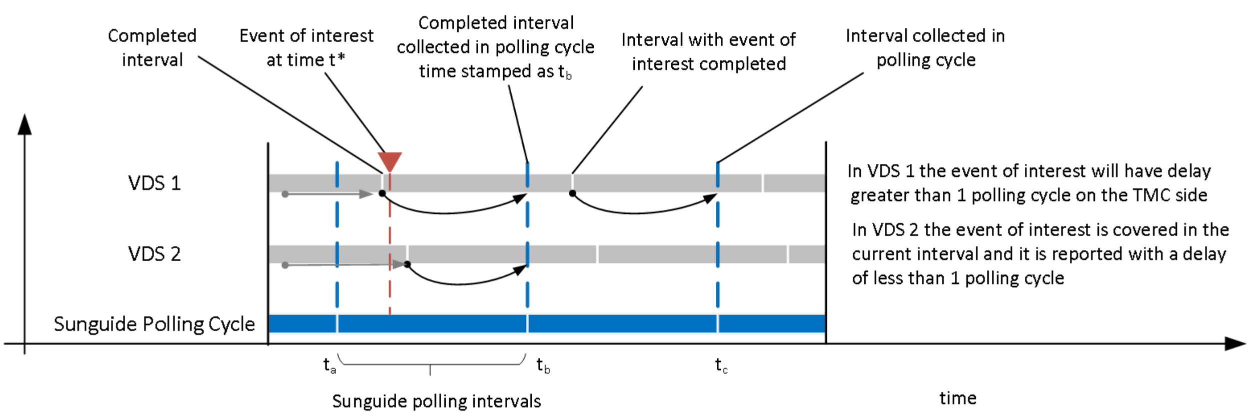


Figure 76: Expected Data Synchronization Delays in the Polling System

To better characterize the effect on clock synchronization on TMC applications, the aggregation interval length was divided by the polling cycle time. This ratio is denoted as CA-ratio (cycle to aggregation interval ratio). Table 27 presents the calculated CA-ratios for volume accuracy for the example in Figure 73. Using a cycle time of one minute with an aggregation interval of 60 minutes gives a CA-ratio of two percent. Under this condition, the best accuracy after synchronization was 94% and the accuracy at 0-lag (no sync) was 94.3%. The difference in percentage points is 0.3, which is equivalent to a 0.4% degradation in accuracy. Given the same amount of lag or delay in the case of the sample MVDS it was observed that for large aggregation intervals the degradation in accuracy is less than one percent. As the aggregation interval gets closer to the polling cycle, the degradation in accuracy becomes more noticeable.

Table 27: CA-Ratios for Volume Accuracy

Aggregation Interval	Cycle to Aggregation Interval Ratio	Accuracy at 0 Lag	Best Accuracy	Percentage Points	Percent Degradation
60	2%	94.0%	94.3%	0.3	0.4%
15	7%	89.5%	92.6%	3.1	3.4%
5	20%	74.8%	87.5%	12.71	14.5%

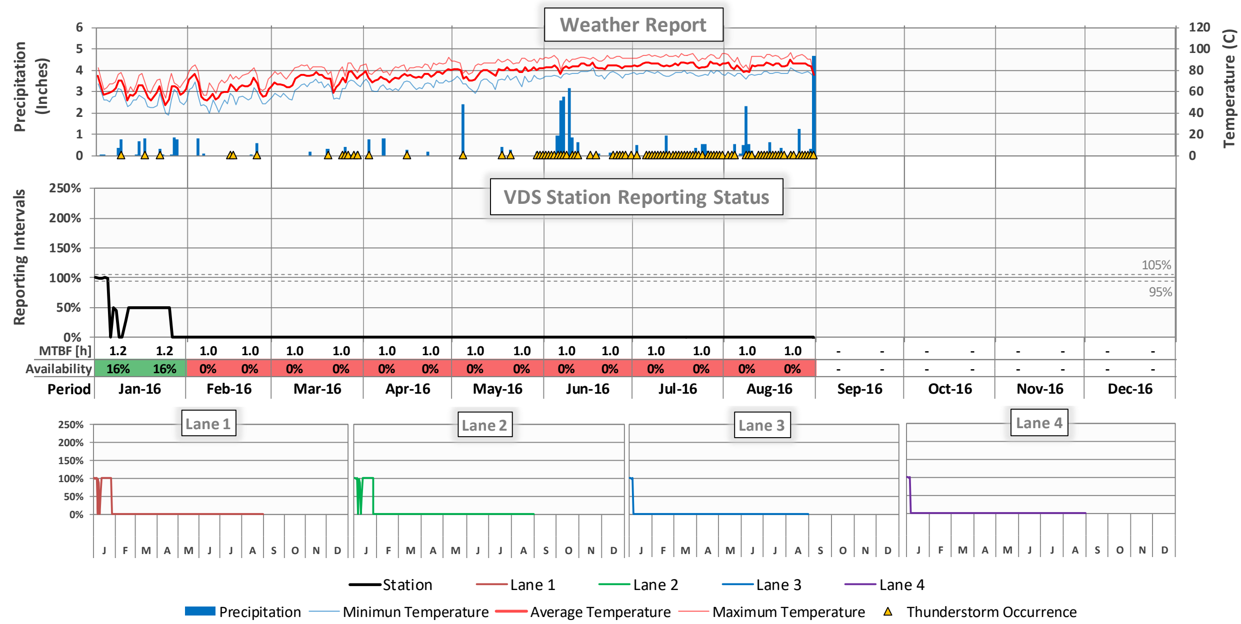
The objective of the CA-ratio is to quantify the degradation on volume accuracy with respect to configuration parameters such as polling cycle and aggregation interval. Smaller CA-ratios can be obtained by using shorter polling cycles and long aggregation intervals. Transportation planning applications aggregating volume and speed data on an hourly or daily basis will not be affected by time synchronization issues. Applications consuming intermediate time aggregated data (e.g., 15 minutes) will be slightly affected by time lags. These applications include travel time and express lane management. Applications requiring shorter levels of aggregation such as queue detection may be noticeable affected. To alleviate this, reduced CA-ratios and periodic time synchronization are recommended.

There may be multiple causes of time discrepancies in VDS data including configuration, hardware, and software issues. Combinations of polling cycle length, MVDS clock out of sync, network delays, network packet loss, and processing delays in the polling system can cause time lags. Attenuation strategies may include synching VDS clocks at least once a day, use polling cycle of less than one minute. Also reviewing the data workflow looking for possible processing delays and allocating more resources to the polling system may be considered

5.3.3 Interval Reporting Verification

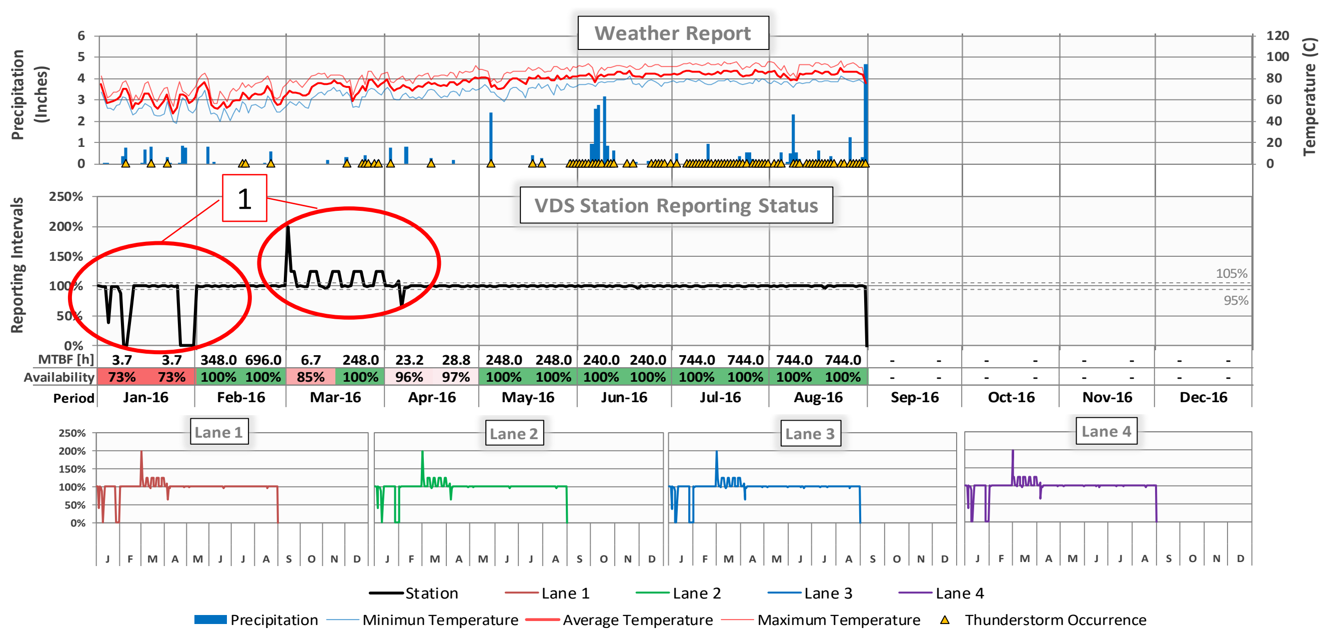
The first step into analyzing the data were verifying the detector availability during the entire period. To verify the availability, this research relies on the fact that, since the data were reported in 1-minute intervals, it was expected that each hour of data should contain 60 timestamped records of reported volumes, speeds, and occupancy. Following the same logic, each day should have 1440 records for each lane. The amount of reported intervals was summarized by day and the percentage of reported intervals was calculated. Figures 77 to 79 present the findings for 2016. The top part of each chart presents the weather condition in a daily basis, including temperature and precipitation for all years and the occurrence of thunderstorms in 2016 (*43*). The same type of analysis was performed also for 2014 and 2015.

To obtain a quantitative measure of the reporting performance of each detector, the mean time between failures (MTBF) and the availability were calculated and presented under each chart in the respective months. Two different definitions of error were used to calculate the two indicators. The first one (leftmost value within each month) is more restrictive and considers as failure any period where the amount of reported records are outside a 5% acceptance region (from 57 to 63 intervals per hour). The second definition assumes that over reporting isn't as severe of an error as under reporting is, since no data are lost in this case and simple processing can remove the duplicated records.



*MTBF/Avaiability use two definitions of failure: 1) Data points outside the 95%,105% interval (leftmost column within each month). 2) Data points under 95% (rightmost column within each month).

Figure 77: Detector Reporting Measurement: Count Station 2016



*MTBF/Avaiability use two definitions of failure: 1) Data points outside the 95%,105% interval (leftmost column within each month). 2) Data points under 95% (rightmost column within each month).

Figure 78: Detector Reporting Measurement: Wavetronix HD 2016

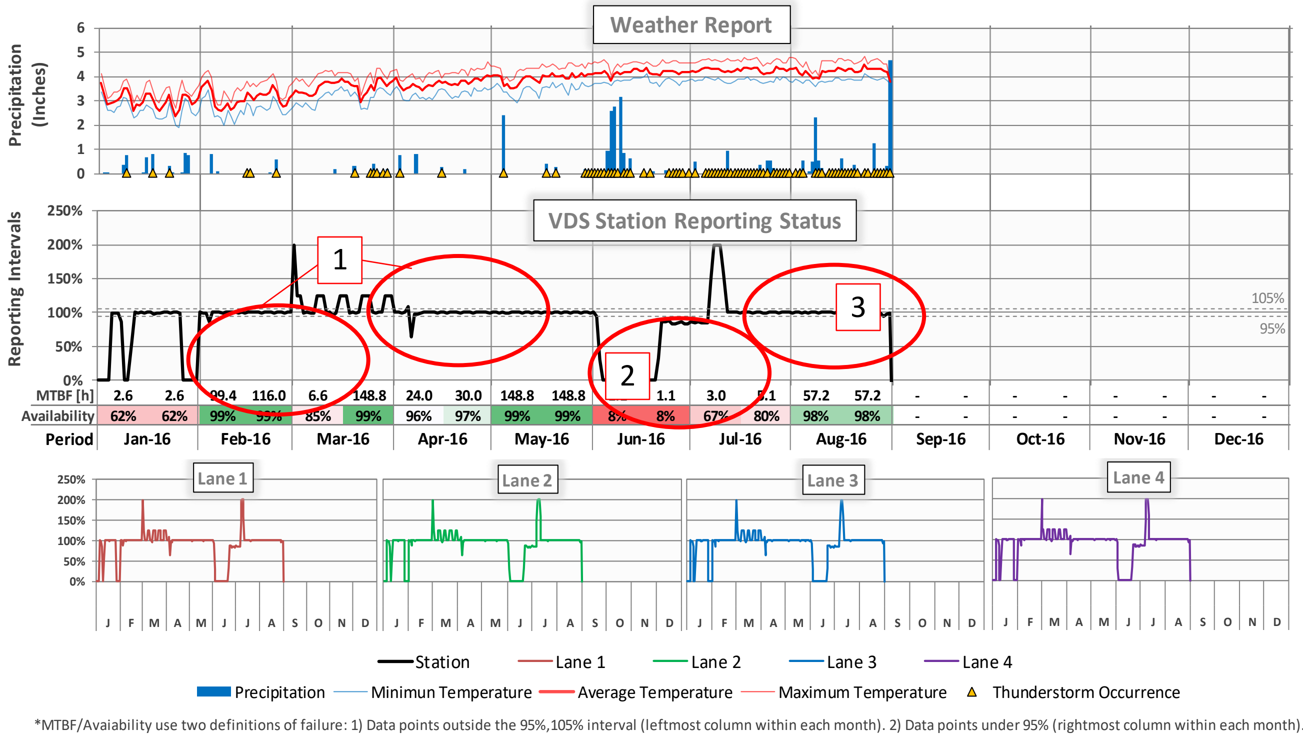


Figure 79: Detector Reporting Measurement: ISS G4 2016

Following the indications given by the plots, periods of interest were selected so that the data could be analyzed in more depth to explain the reasons behind double reported (over 100%) and missed intervals (under 100%).

The Wavetronix HD and the ISS G4 charts show strong correlation in the reported interval errors for the months of January and March (Figure 78 and Figure 79, box 1), which suggests that the errors weren't generated in the detector itself but during processing or storage, differently than the errors that are exclusive of the ISS G4 during June and August (Figure 79, boxes 2 and 3).

The Wavetronix HD and the ISS G4 data sets also contain a time synchronization issue; the timestamps in the saved data are constantly drifting. On average one extra second is added to the timestamp each 65 seconds. This type of error induces intervals to be skipped. To exemplify the occurrence of this error, an excerpt from the data are reproduced in Figure 80. The *x-axis* indicates the length of the intervals, while the triangles indicate the VDS data timestamp. The first row (from 12:00 p.m. to 12:10 p.m. on the 01/01/2016) show that the data were timestamped roughly in the middle of the intervals. In fact the timestamp for the first triangle is 12:00:39 p.m. The second row (from 00:00 a.m. to 00:10 a.m. on the 01/02/2016) shows the effect of the drifting twelve hours later. Now the timestamp is saved at 00:00:50 a.m. The third row shows the effect of the drifting, resulting in skipping interval 09:39:00 a.m. on the 01/02/2016.

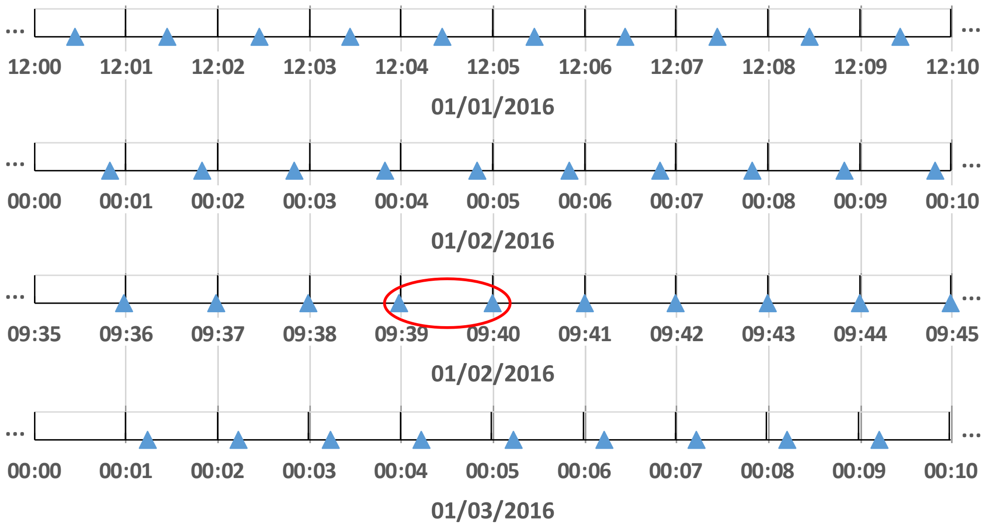


Figure 80: Interval Synchronization Error (HD and G4)

Figure 81 shows the excerpt from the Wavetronix HD data set where this particular interval is skipped. Given that rate, we should expect that more than 20 intervals will be skipped per day.

ID	VDS_DATE	TIMESTAMP	VDS_NAME	VDS_LANE	SPEED	VOLUME	OCC
119463	02/01/2016 00:00	09:34:59.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	70	6	2
119523	02/01/2016 00:00	09:35:59.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	72	5	2
119579	02/01/2016 00:00	09:36:59.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	66	1	0
73867	02/01/2016 00:00	09:37:59.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	67	4	2
73918	02/01/2016 00:00	09:38:59.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	69	6	2
73975	02/01/2016 00:00	09:40:00.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	76	2	1
74038	02/01/2016 00:00	09:41:00.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	66	1	0
74075	02/01/2016 00:00	09:42:00.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	61	2	1
74138	02/01/2016 00:00	09:43:00.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	75	3	1
82459	02/01/2016 00:00	09:44:00.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	70	2	1
82536	02/01/2016 00:00	09:45:00.0	MVDS I-275 28.4 SB HD	MVDS I-275 28.4 SB HD-L1-ln1	77	5	2

Figure 81: Data Excerpt: Interval Skipping

The analyses presented in the sequence exclude the duplicated records from all sources. On the other extra readings are maintained and considered as part of the closest interval. Interval skipping is also reflected on the data, since it is inherent to the data set.

5.3.4 VDS Performance Analysis

This aggregated analysis was based on VDS detection periods selected from the available data described in the previous section. The data sets were mapped and subsets of data were generated to include only the full 24-hours periods where there was data reported for all four detection technologies. From these subsets two 24-hours periods were chosen and a detailed analysis was performed for days 08/29/2014 and 01/05/2016. The source of ground truth comes from the count station installed in the testbed, using inductive loops.

Figure 82 shows VDS reported five-minute volume versus ground truth for each detector in 2014. Figure 82(a) and Figure 82(b) show that the Wavetronix HD and the ISS G4 have strong linear relationships with the ground truth volume. The correlation coefficients are 0.96 for the Wavetronix HD and 0.94 for the ISS G4. It is also noticeable that the variability in the relative error increases when the traffic density is higher.

Similarly, Figure 83 shows VDS reported five-minute volume versus ground truth for each detector but for the second period in 2016. Figure 83(a) and Figure 83(b) show that, similarly to the first period, the Wavetronix HD and the ISS G4 have strong linear relationships with the ground truth volume. The correlation coefficients are 0.96 for the Wavetronix HD and 0.98 for the ISS G4. Once again the variability in the relative error increases when the traffic density is higher. The Autoscope had again the worst performance with the highest variability and lowest correlation coefficient of 0.76. There is again strong indication that lane 1 needs calibration, but this time there is a high incidence of overcounts.

Figure 84 and Figure 85 show the same type of analysis but in a fifteen-minute aggregation level, the increase in the length of time for the aggregation will have a tendency to narrow the data around the true value for data sets that have errors symmetrically distributed around this true value. This process of smoothing out the error can be observed in Figure 84(a), (b) and Figure 85(a), (b). In fact, the correlation coefficients for the Wavetronix HD and the ISS G4 were approximately 0.99 in all cases.

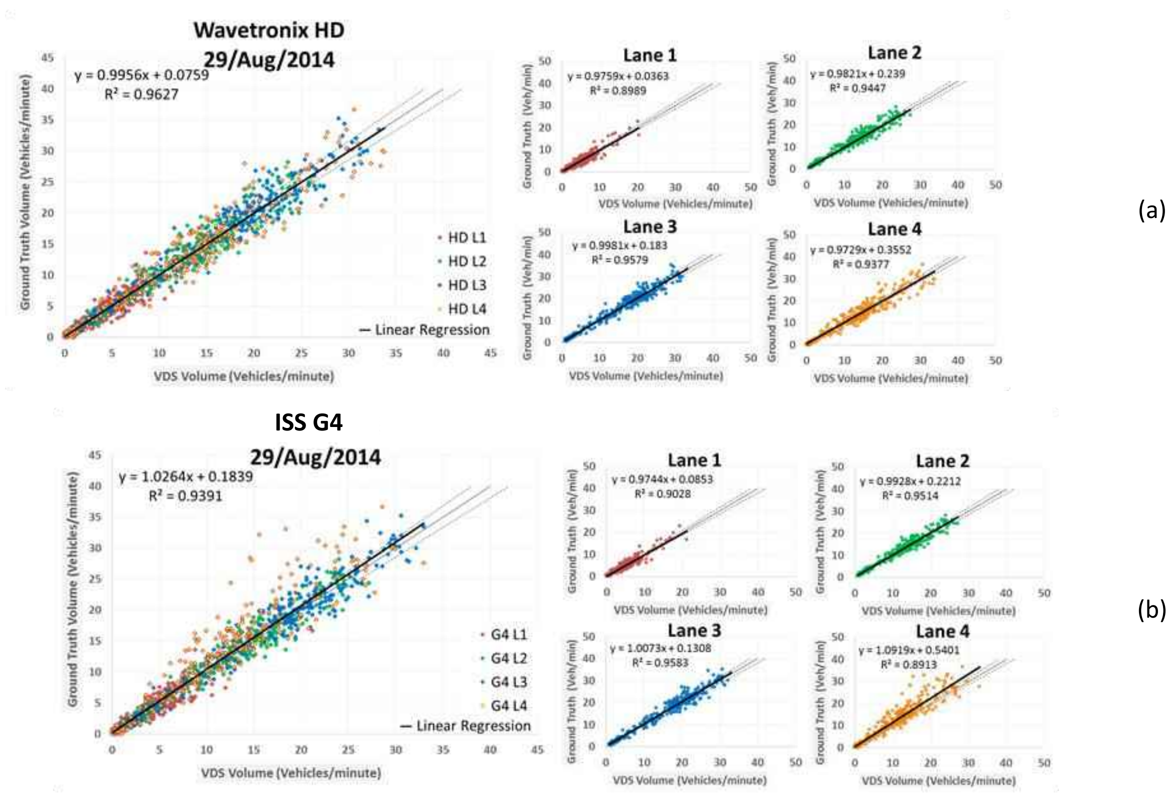
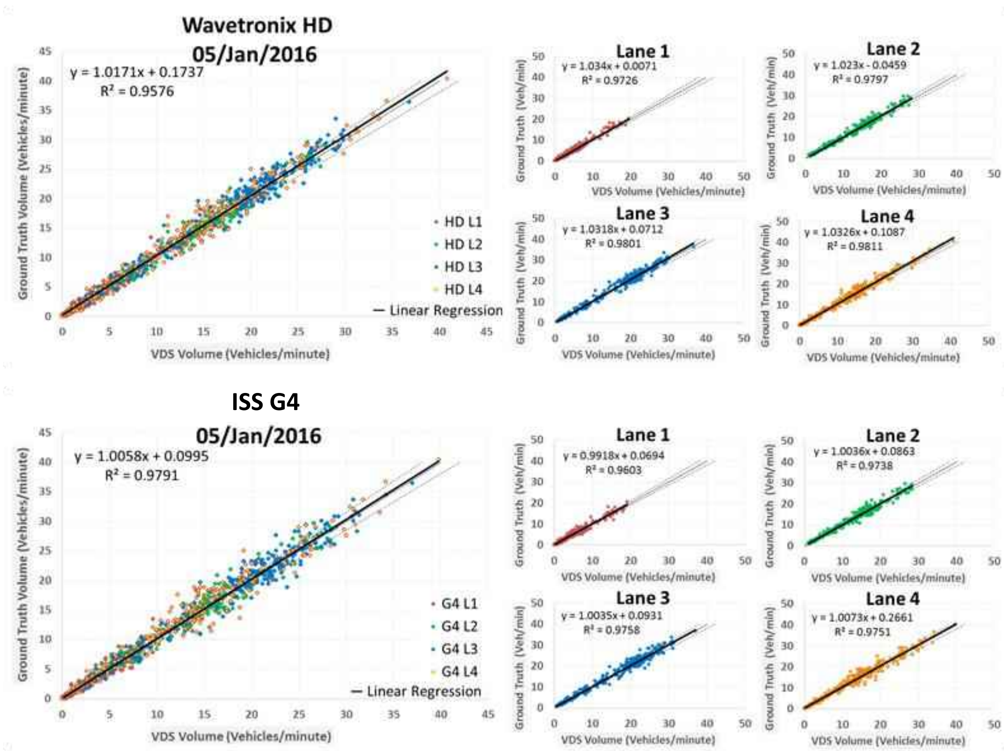


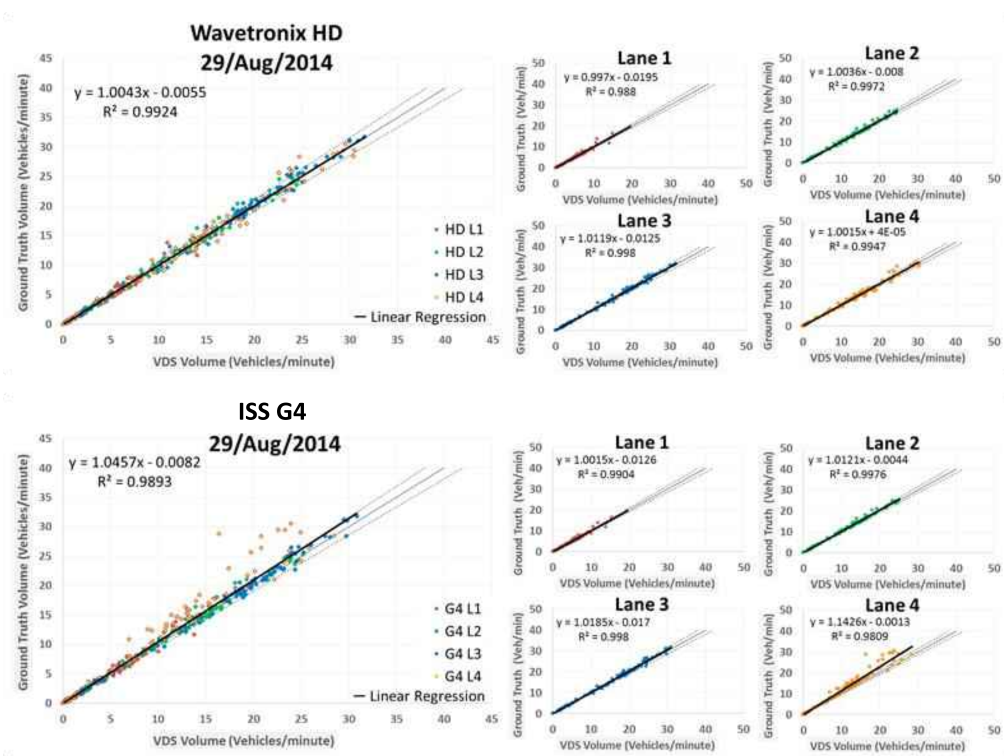
Figure 82: 5-Minute Volume Scatter Plots against Ground Truth for Wavetronix HD (a), and ISS G4 (b), 2014



(a)

(b)

Figure 83: Five-Minute Volume Scatter Plots against Ground Truth for Wavetronix HD (a), and ISS G4 (b), 2016



(a)

(b)

Figure 84: 15 Minute Volume Scatter Plots against Ground Truth for Wavetronix HD (a), and ISS G4 (b), 2014

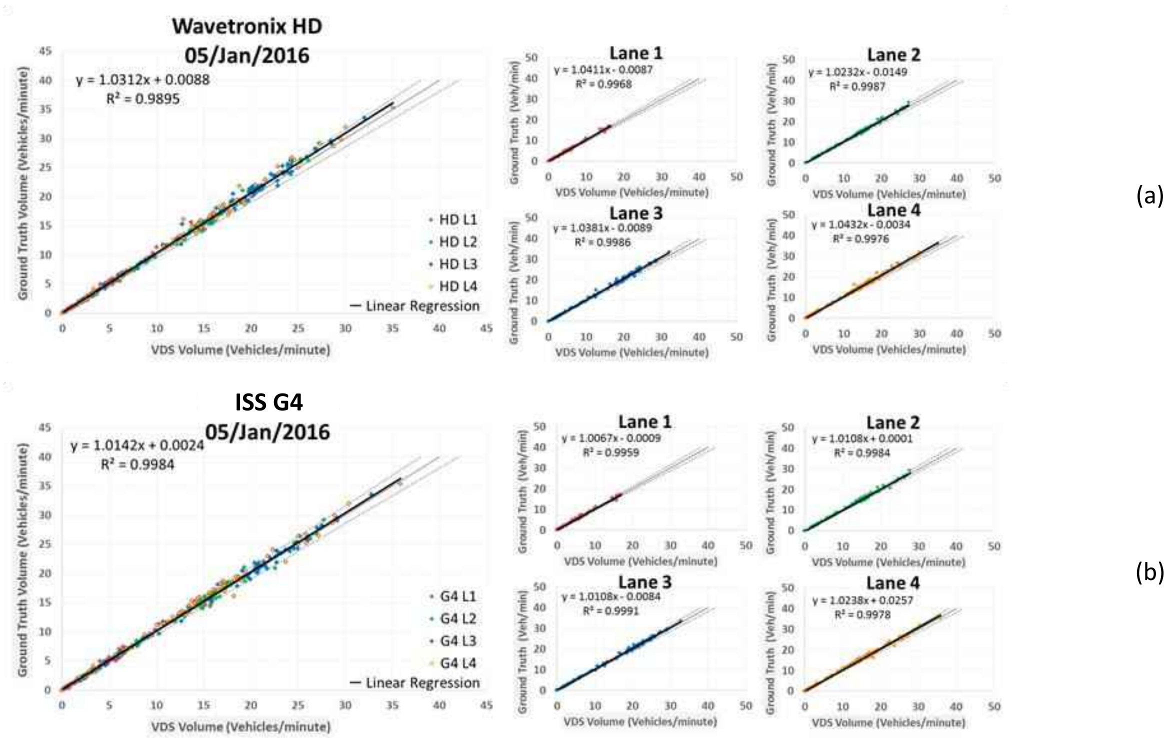
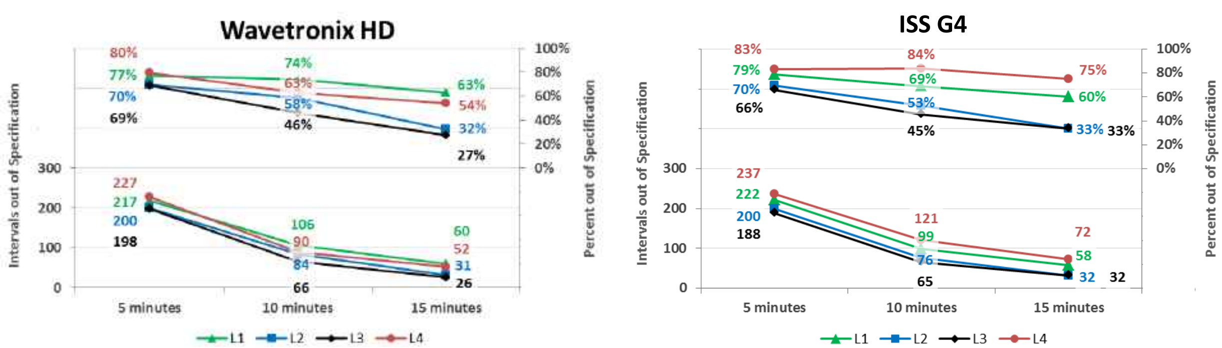


Figure 85 : 15- Minute Volume Scatter Plots against Ground Truth for Wavetronix HD (a), and ISS G4 (b) 2016

Figure 86 shows that increasing the aggregation level led to a reduction in the amount of absolute intervals out of specification. The charts presented here are for the 08/29/2014 data set. The same conclusions are applicable to the 01/05/2016 data set that was omitted her due to their similarity. The relative percentage of intervals out of specification also had a significant reduction for the Wavetronix HD and the ISS G4. Another interesting aspect is that lanes 2 and three (center lanes) consistently present smaller amount of out of specification intervals. Lanes 1 and 4 (outside lanes) systematically have higher incidence of intervals out of specification.

Figure 87 brings detailed aspects of the data summarized in Figure 86 by showing occurrences and magnitude of error for each interval out of specification.



(a) (b)

Figure 86: Effect of Aggregation Level for the 08/29/2014 data

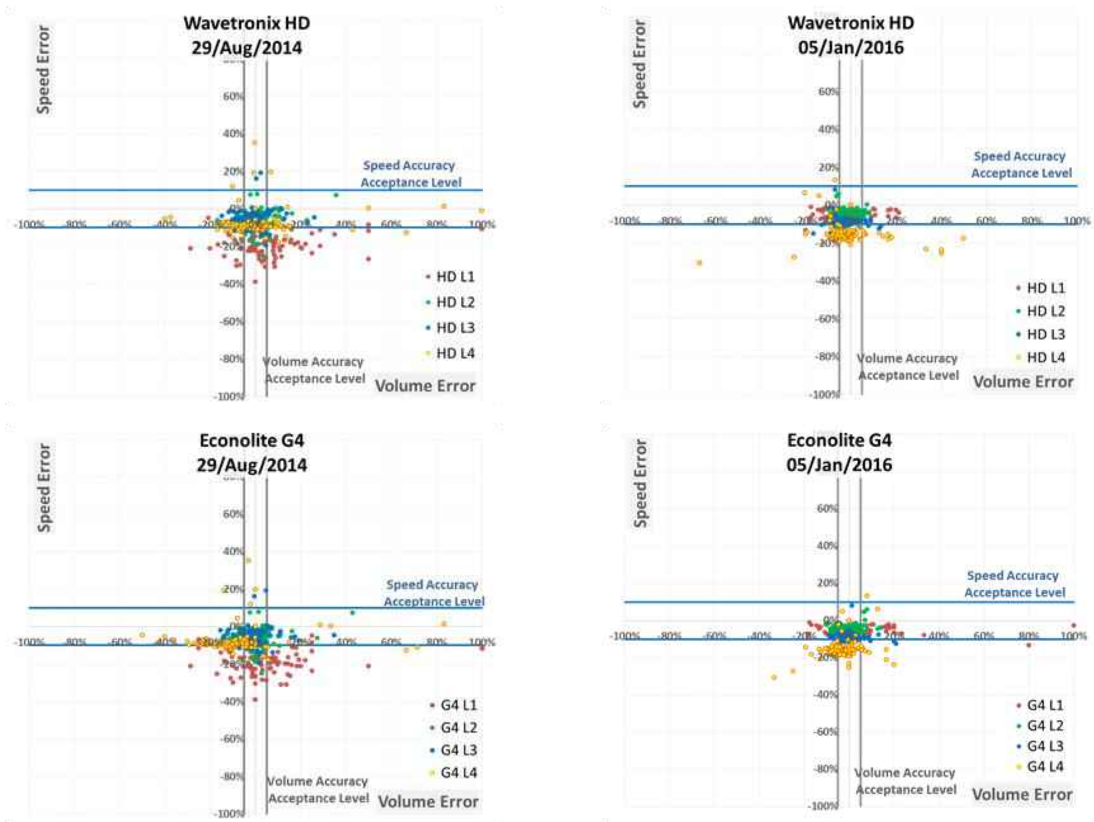


Figure 87: Scatter Plot: 15-minute Aggregated Speed and Volume Accuracy Fluctuation for Wavetronix HD (a), ISSS G4 (b)

The y-axis shows speed error and the x-axis show the volume error. The blue horizontal lines indicate the speed accuracy acceptance level and the gray lines indicate the volume accuracy acceptance level. For an interval to be considered within specification it must be located inside the rectangle formed by the intersection of these lines. The charts indicate that volume errors tend to be symmetrical around the true value, while speeds were systematically under estimated. Figure 87(a) and Figure 87(b) clearly show that lanes 1 and 4 tend to be out of specification more often, while lanes 2 and 3 are more accurate and consistent around the true values for speed and volume.

5.3.5 Specification 660 Accuracy Acceptance Tests Application

This section applies the volume and speed accuracy acceptance tests required for VDS acceptance in Florida .The extensive data analyses generated for two 24-hour periods gives an excellent reference to assess how effectively the proposed tests are capable of detecting performance degradation.

Figure 88 depicts the volume accuracy values obtained for the 29/Aug/2014 Wavetronix HD data set. Each one of the nine columns indicate the predefined periods of the day, as defined in specification 660. The rows hold each volume accuracy calculation previously to the application of the final equation to calculate the 24-hour period accuracy error. The requirements specify that at least one 15-minute interval must be sampled for the EM, AMP, LAOP, NO, AOP, PMP, and NI period, and two 15-minute intervals must be sample for the DA and DU periods.

Thirty events were simulated for each detector to mimic the behavior of the test in practical applications. Each one of these events randomly selected the intervals to be considered in the calculations. Figure 89(a) presents the simulated events and final volume accuracy obtained for the 29/Aug/2014 data set and Figure 89(b) presents the results for the 05/Jan/2016 data set.

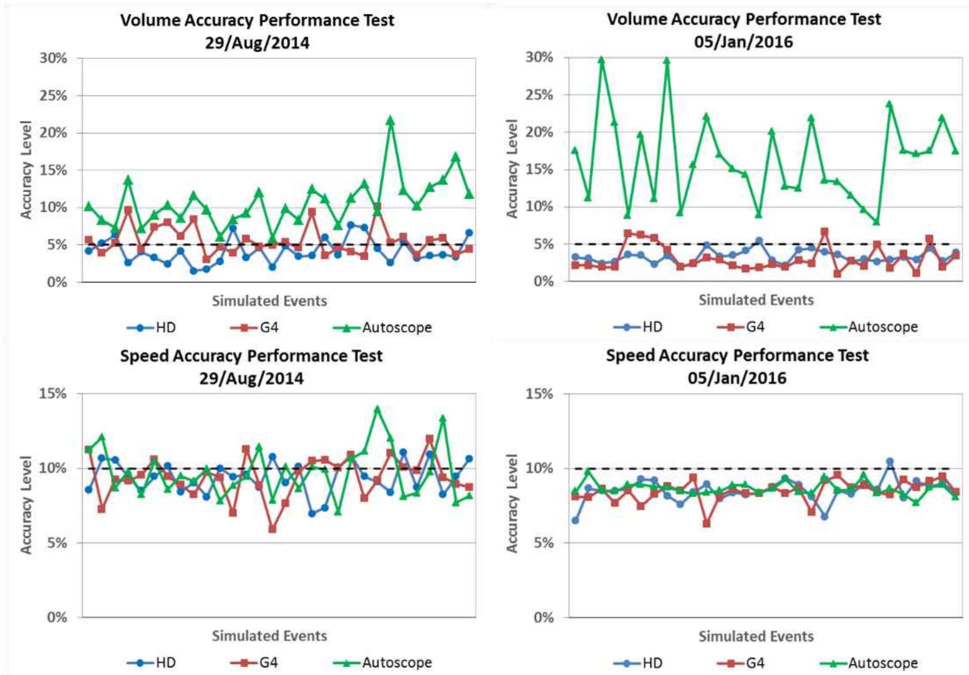
	12:30 a.m. 6:30 a.m. EM	6:30 a.m. 7:00 a.m. DA	7:00 a.m. 8:00 a.m. AMP	8:00 a.m. 12:00 p.m. LAOP	12:00 p.m. 1:00 p.m. NO	1:00 p.m. 5:00 p.m. AOP	5:00 p.m. 6:00 p.m. PMP	6:00 p.m. 6:30 p.m. DU	6:30 p.m. 12:30 a.m. NI
1	0.7%	2.0%	1.3%	7.8%	2.3%	0.5%	4.5%	10.5%	5.1%
2	5.1%	3.8%	4.8%	6.8%	2.2%	1.1%	9.1%	0.1%	0.6%
3	0.9%		2.8%	0.6%	2.4%	0.4%	2.8%		6.4%
4	16.9%		-	0.8%	0.1%	3.1%	3.1%		0.2%
5	7.1%			1.1%		1.1%			5.8%
6	22.0%			2.3%		3.3%			2.5%
7	8.1%			3.7%		0.4%			3.9%
8	4.2%			6.3%		3.5%			2.1%
9	6.1%			2.4%		8.3%			0.3%
10	8.9%			2.7%		1.3%			10.5%
11	0.0%			0.6%		1.0%			8.5%
12	0.0%			2.4%		1.3%			7.0%
13	11.1%			0.7%		2.2%			0.8%
14	1.5%			1.9%		1.9%			5.6%
15	11.3%			1.0%		2.1%			3.4%
16	1.4%			8.8%		6.3%			2.7%
17	9.7%								5.9%
18	3.1%								5.4%
19	2.0%								2.5%
20	0.5%								10.9%
21	4.6%								7.4%
22	7.1%								-
23	9.1%								-
24	1.5%								-
Out of Spec.	50%	0%	0%	25%	0%	13%	25%	50%	52%

Color Code:
Black: Within Specification
Red: Out of Specifiation

Figure 88: Volume Accuracy for the Wavetronix HD 29/Aug/2014

For both data sets, the method rejected 100% of the simulated intervals for the Autoscope, regarding volume accuracy. This result was expected, given the errors found in the VDS detections, and shows that the accuracy acceptance test is capable of detecting errors of the magnitude presented by the Autoscope. The volume readings for the Wavetronix HD and ISS G4 were found to be more accurate, as shown in Figure 82-Figure 85 and Figure 87. As expected, the acceptance tests didn't reject most of the simulated events. In fact, out of the 120 simulated events for the two detectors, 91 would be approved. It is expected that in testing detectors with similar performance for volumes, over 76% of the time the detectors would be approved. Regarding speed acceptance tests, even though all detectors are systematically underestimating, 148 out of 180 simulated events would not be rejected by the test. It is expected that in testing detectors with similar performance for speeds, over 82% of the time the detectors would be approved. The rejected events are concentrated in the 2014 data set. Only one simulated event would be rejected for the 2016 data set.

1

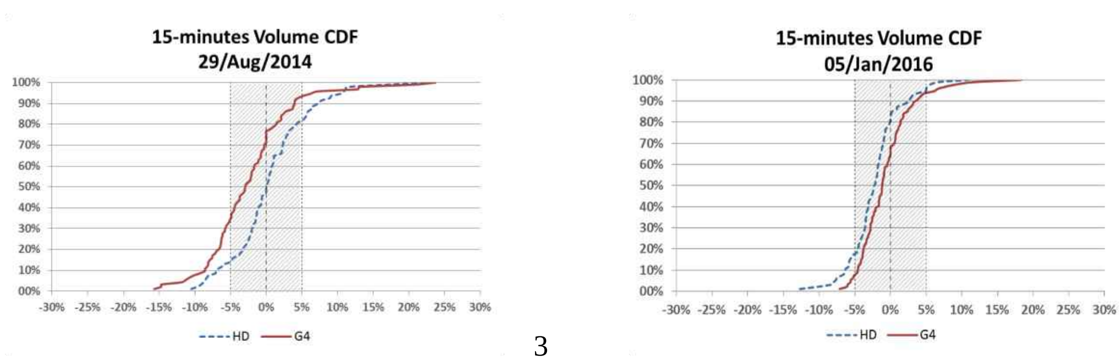


(a) (b)

Figure 89: Volume Accuracy Acceptance Test Performance for (a) 29/Aug/2014 and (b) 05/Jan/2016

Figure 90 shows a cumulative distribution plot of the 15-minute volume accuracy when compared to the ground truth for the Wavetronix HD and ISS G4. The plots show that both detectors have similar distributions, symmetrically distributed around the target. It is also noticeable a significant improvement in accuracy from 2014 to 2016. The lower end of the distributions in Figure 90(a) show that the G4 presented more undercount errors than the HD, while in the upper end the G4 detector outperformed the HD, indicating less occurrences of overcounting errors. The lower end of the distributions in Figure 90(b) show that the G4 presented less undercount errors than the HD, while in the upper end the HD detector outperformed the G4, indicating less occurrences of overcounting errors.

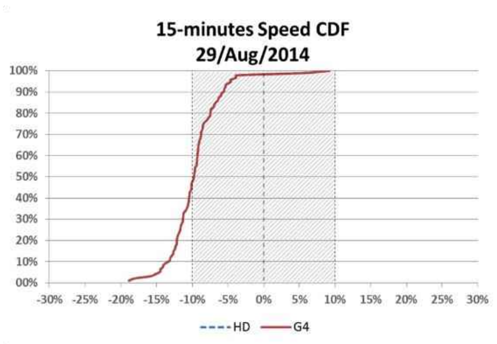
2 3

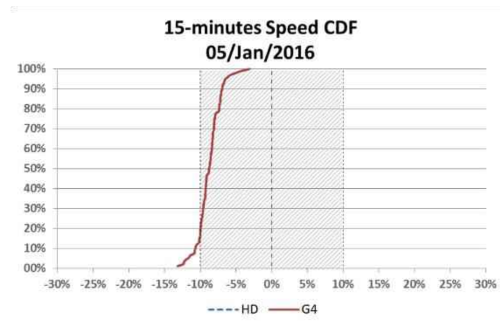


(a) (b)

Figure 90: Cumulative Distribution of 15-minute Volume Accuracy Distribution for (a) 29/Aug/2014 and (b) 05/Jan/2016

Figure 91 shows the cumulative distribution plots of the 15-minute speed accuracy when compared to the ground truth for the Wavetronix HD and ISS G4. The plots show that both detectors have almost identical distributions. Confirming the previous findings, both distributions indicate systematic underestimation of speeds. From 2014 to 2016 there was an improvement in accuracy, given by the reduction of the percentage of intervals out of specification.

4 

5 

(a) (b)

Figure 91: Cumulative Distribution of 15-minute Speed Accuracy Distribution for (a) 29/Aug/2014 and (b) 05/Jan/2016

6 Application of Micro-simulation Modeling

This section is dedicated to the application of traffic microscopic simulation modeling, using VISSIM, to model traffic on a road network of interest. In doing so, we seek to evaluate real-time effects of VDS performance degradation and its effects in traffic management strategies, given alternative traffic scenarios.

The chosen approach is to model the southbound direction of the road segment in the Vero Beach corridor using VISSIM. The 9-mile long segment was modeled, including the nine vehicle detection stations, positioned across the segment as described in Figure 52 . The simulation model is created to accept individual input per lane. Each vehicle detection station also records the lane in which the detection took place. In that sense, the data collected from the simulation includes, for each vehicle, timestamps in each of the nine detectors, vehicle speed, acceleration, and length.

The input data for the simulation model comes from real traffic data, from the SunGuide database, so that each lane independently received traffic pattern inputs (vehicles per minute, speed distribution, and vehicle length) based on historical traffic data. In the same sense, the VDS performance degradation is simulated using error found in real traffic data.

Figure 92 presents a macroscopic view of the system, defining the relation between the sources of data and the main functions within each one of the parts of the system in Excel, VISSIM, and Access. The input data for the simulation model comes from the SunGuide database. The data are made available per lane in 1-minute intervals including timestamps, vehicle counts, average interval speed, and vehicle classification in length bins. The data set is organized using Excel to fit the needs of the simulation model. Using Visual Basic for Applications (VBA) as interface, the input data (speed, volume, and vehicle type) is streamed to VISSIM during the simulation run. After the simulation is completed, the output data are saved to an access database in the vehicle level. The raw data are processed using Structure Query Language (SQL) to mimic the Travel Time Posting Pricing Strategies in Tolling Applications. The output of this process is then exported back to Excel using VBA. These data sets are the ground truth values for the two applications: travel time and toll pricing, since all calculations were performed using perfect information from the simulated VDS.

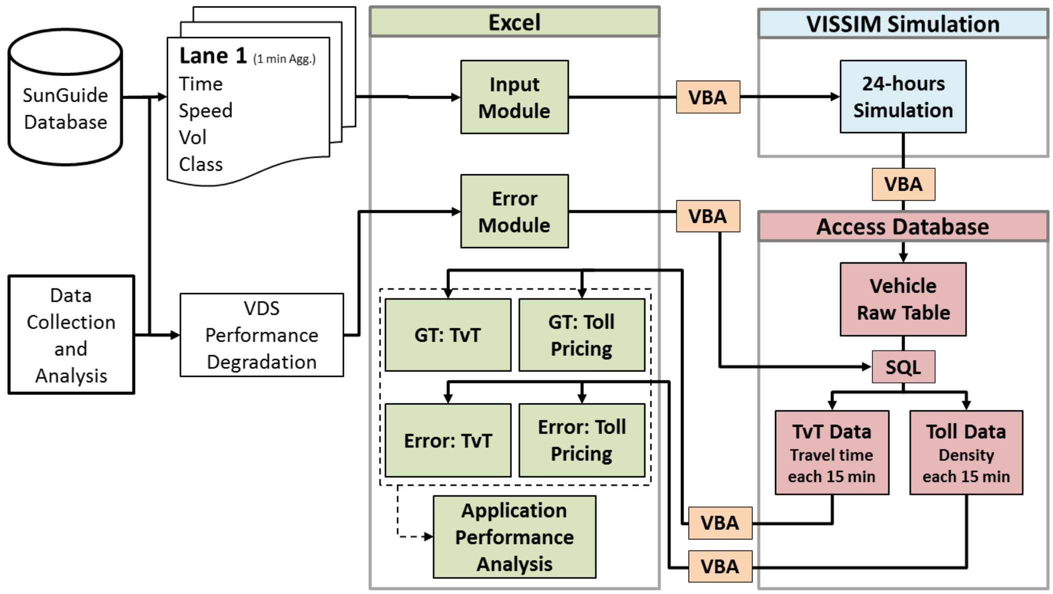


Figure 92: Macro View of the Application Performance Simulation System

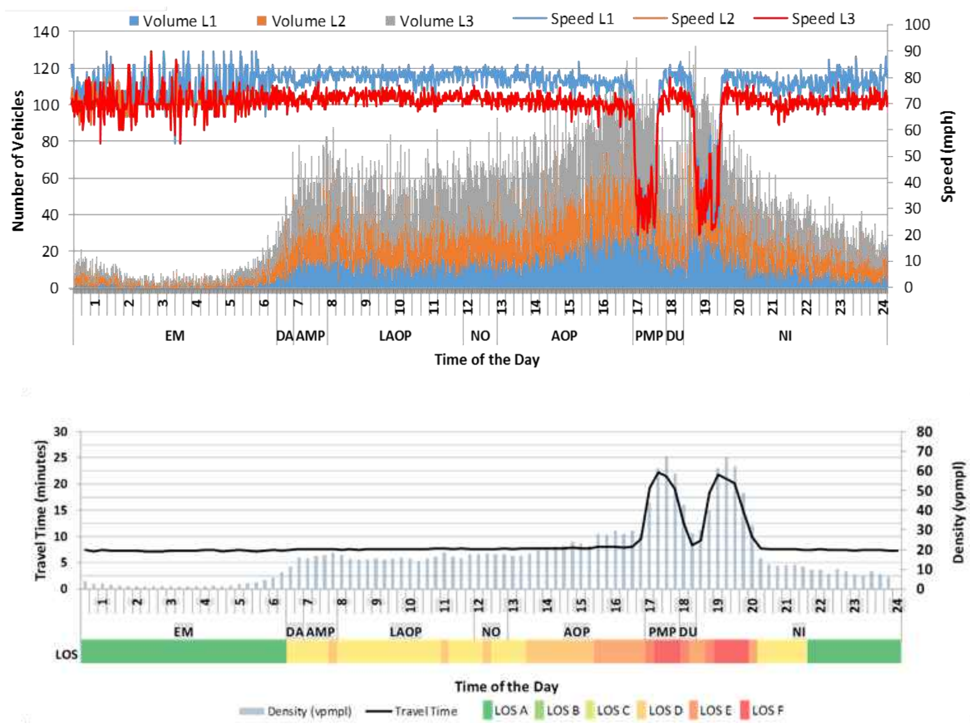
The next step is to estimate the effect of VDS performance degradation in the applications. In order to do so, the accuracy degradation simulation module in Excel is activate, feeding the VDS performance degradation into the appropriated tables in the database and the queries are run again to perform the new travel time and toll pricing calculations, but this time factoring the simulated error in the process. The last step is to compare and analyze application performance, under alternative scenarios and different VDS performance degradation levels.

6.1 Verification and Validation

In using micro-simulation models, it is necessary to ensure that the simulated vehicles activity truly represents the dynamics in the real world. In that sense, verification and validation of the model is a paramount aspect to be considered. According to the definitions adopted in (*44*), model validation is the "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". Model verification is usually defined as the process of ensuring that the computer program applying the model and its implementation were done correctly. In this study we verified and validated our model through a combination of widely adopted techniques.

The first approach was to evaluate the behavior of a simplified model so that the exact expected output of the model could be calculated and then compared to the actual output. At first a single vehicle was generated per lane so that volume and speed readings from the detector were expected to match the ones from the unique vehicles generated. In the same sense, the travel time calculated by the model was compared to the individual vehicle travel times. The density outputs were also checked using the same logic. To complement the analysis and evaluate if the averages and sums were considered properly, five, and ten vehicles per lane were generated in another two experiments and the results again compared.

In the sequence, degenerate tests were conducted by testing the behavior of the system given appropriate changes in the values of the inputs. These tests demonstrated appropriated system responses in specific situations (i.e., inducing reductions in vehicle speeds led to increase in travel times output). To complete the verification and validation analysis, we combined predictive validation and operational graphics. The graphics show system outputs for calculated travel times and density (Figure 93(b)) given specific vehicle volume inputs (Figure 93(a)). The volumes per lane are presented stacked. As demonstrated, both density and travel time outputs behave as expected for the volume and speed profile.



(a)

(b)

Figure 93: Operational Graphics: Model Validation

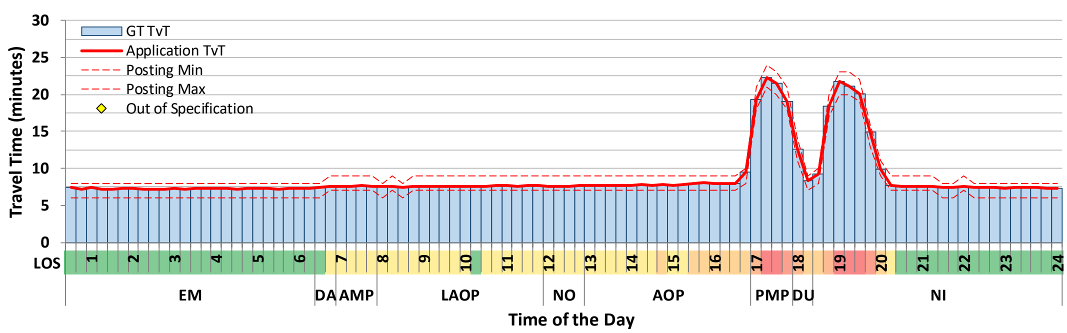
It is noticeable that starting in the afternoon peak period (starting at 5:00 p.m. and represented as PMP in the chart) the speeds drop and the volumes increase in all lanes (Figure 93(a)), reflecting the increase in traffic density of the peak hours. This effect is then correctly estimated by the model and reflected in the calculations depicted graphically in (Figure 93(b)). The travel times increase in that period, as shown by the black line graph. The calculated traffic density also increases, as indicated by the light blue bar chart.

6.2 Travel Time Application

Figure 94 presents the base view for the Travel Time Application output from the system. The top table indicates the simulated errors for speed and volume per lane in each one of the nine links that compose the segment of interest. In the *x-axis* we have the periods of the day, organized in 15-minute intervals, also displaying the separation in periods and used in VDS testing. In the y-axis the travel times are presented in minutes. The bar chart in blue indicates the ground truth travel time considering perfect VDS detections across the segment. The line charts in red are the calculated travel times using simulated VDS accuracy degradation. The continuous line is the value obtained from the formulas while the dashed lines indicate the maximum and minimum travel time values that are posted to the public. Generally the travel times are posted given intervals, instead of spot values. These intervals are created by SunGuide around the calculated value to accommodate for variations. As an example, consider that SunGuide is set to post a three minutes interval for calculated values under 10 minutes and a 4 minutes interval for calculated travel times over 10 minutes. If at certain point the calculated value is seven minutes, the posted travel time would be: “from six to nine minutes”. In case the calculated value was 11 minutes, the posted travel time would be: “from nine to 12 minutes”.

The table in the leftmost bottom part of the figure defines the posting ranges. In the rightmost bottom part of the figure a summary table depicts the intervals out of specification within each period of the day. The chart also uses color code to display the level of service in each 15-minute intervals (LOS A represented in green all the way to LOS F represented in red).

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
L2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
L3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%



SunGuide Parameters	
timeRangInterval1	2 min
timeRangInterval2	3 min
changeRangeInteral	10 min

	Summary: Intervals out of Specification									
	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
#	0	0	0	0	0	0	0	0	0	0
%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

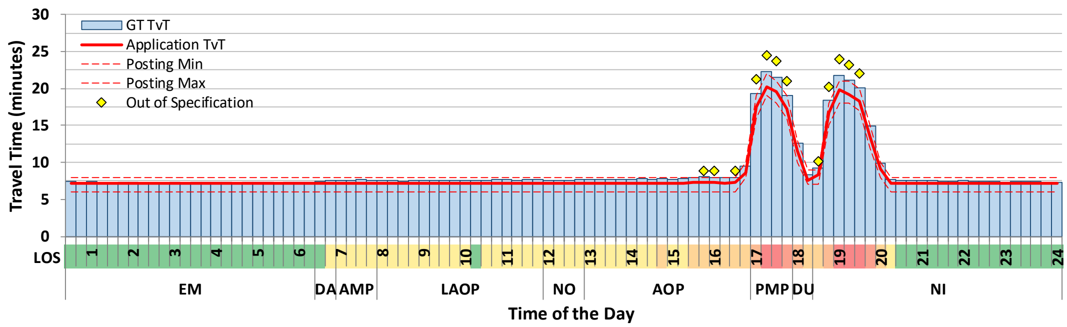
Figure 94: Travel Time Application Output (Perfect VDS Data)

In the situation presented in Figure 94, where there is no VDS error being induced, the travel time application doesn’t present any errors in posting travel times, as expected. It is important to notice that this analysis takes into consideration that the system posts travel times using a two minutes range, for travel times under 10 minutes, and a three minutes range for travel times over this mark.

Next, we would like to understand how the travel time posting application would be affected by the extreme situation where all detectors have accuracy exactly at the limits stablished in the

Specification 660 (*9*). In order to do so, four scenarios were created where speed and volume accuracy $\{Speed_{Acc}, Volume_{Acc}\}$ of all detectors were set to $\{10\%, 5\%\}, \{10\%, -5\%\}, \{-10\%, 5\%\}, \{-10\%, -5\%\}$. Since the travel time is calculated based on a weighted average of volumes, the scenarios could be potentially reduced by two, only depending on the effects due to the error in speed. The results are presented in the sequence in Figure 95 and Figure 96.

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%
L2	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%
L3	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%	10.0%	5.0%

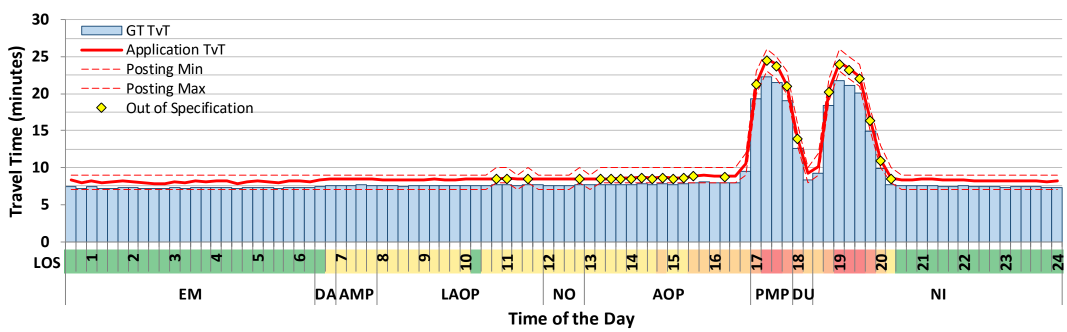


SunGuide Parameters	
timeRangInterval1	2 min
timeRangInterval2	3 min
changeRangeInteral	10 min

Summary: Intervals out of Specification	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
#	0	0	0	0	0	3	4	0	5	12
%	0.0%	0.0%	0.0%	0.0%	0.0%	3.1%	4.2%	0.0%	5.2%	12.5%

Figure 95: Travel Time Application Output (Errors of 10% in Speed and 5% in Volume)

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%
L2	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%
L3	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%	-10.0%	5.0%



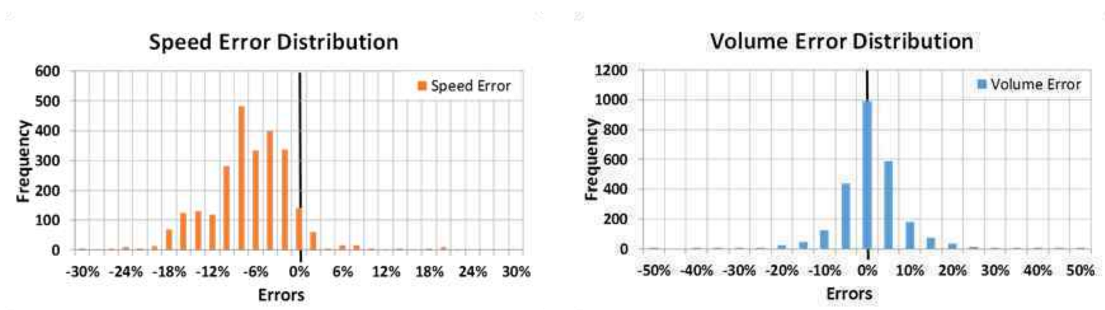
SunGuide Parameters	
timeRangInterval1	2 min
timeRangInterval2	3 min
changeRangeInteral	10 min

Summary: Intervals out of Specification	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
#	0	0	0	3	1	11	4	1	7	27
%	0.0%	0.0%	0.0%	3.1%	1.0%	11.5%	4.2%	1.0%	7.3%	28.1%

Figure 96: Travel Time Application Output (Errors of -10% in Speed and 5% in Volume)

Figure 95 and Figure 96 show that, having all the detectors on the segment in the extremes of the acceptance level, the travel time application would have some loss in performance. For a speed increase of 10% in all VDS, 12.5% of the 96 15-minute intervals would be out of specification. For a speed reduction of 10% in all VDS, 28.1% of the 96 15-minute intervals would be out of specification.

The previous analysis shows that relying on individual VDS acceptance tests may not be enough to guarantee good quality in the system outputs. In addition to defining in the specification VDS unity testing requirements, the system could benefit from requirements that specify minimum performance levels from the application perspective. In this case, given that a travel time application relies on the data provided by nine detectors, one could consider a requirement somewhat similar to: "The number of 15-minute intervals in any given 24-hours period, for which the posted travel time intervals contain the true travel time value shall be at least 91 (95% conformance or higher)". Considering that this requirement is in place, the segment as a whole would fail the performance test and detectors in the segment would need to be calibrated so that the system performance requirement is met. Up to this point, the analysis considering the extreme points of the specification is useful to illustrate the concept previously discussed but it is a scenario very unlikely to happen. In the sequence we simulate the VDS errors based on the data and findings from Chapter 4. The detailed error distributions are shown in Figure 97.

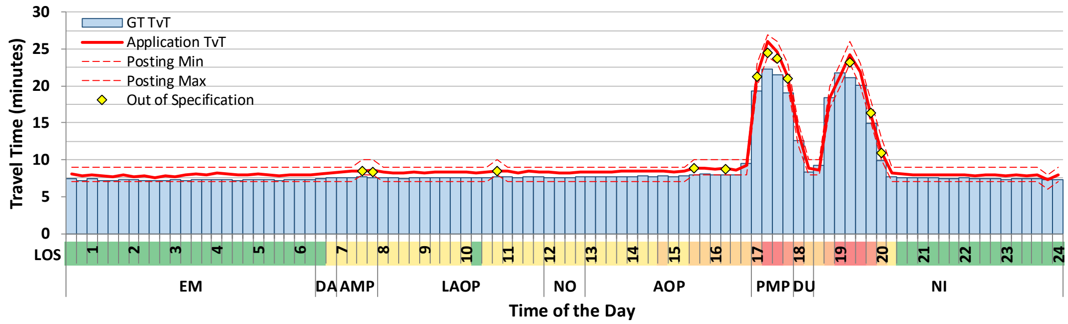


(a) **(b)**

Figure 97: Speed and Volume Error Distribution: Real VDS Errors

Applying these errors to the model, the system would behave as shown in Figure 98 for the travel time estimations. As we can see, there are four lanes out of specification for speed and two lanes out of specification for volume. Nevertheless, since the absolute error per lane is averaged across the station, no detectors would be reject in the tests defined in Specification 660 (*9*). It is noticeable that the speed error distribution is shifted towards underestimation of speeds (Figure 97(a)), what is reflected on the out of specification intervals, since the minimum value in the posted intervals is higher than the true travel time.

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	-7.5%	2.4%	-7.5%	-6.3%	-15.2%	-1.8%	-15.2%	-3.0%	-7.5%	2.4%	-7.5%	-6.4%	-15.4%	-1.7%	-15.3%	-3.0%	-7.5%	2.4%
L2	-4.8%	-0.1%	-4.8%	-0.3%	-8.8%	-2.6%	-8.8%	0.0%	-4.8%	0.0%	-4.7%	-0.1%	-8.9%	-2.7%	-8.8%	0.1%	-4.8%	0.0%
L3	-6.2%	0.6%	-6.2%	-0.2%	-4.4%	-1.3%	-4.4%	-0.7%	-6.2%	0.7%	-6.3%	-0.1%	-4.4%	-1.2%	-4.4%	-0.6%	-6.2%	0.5%



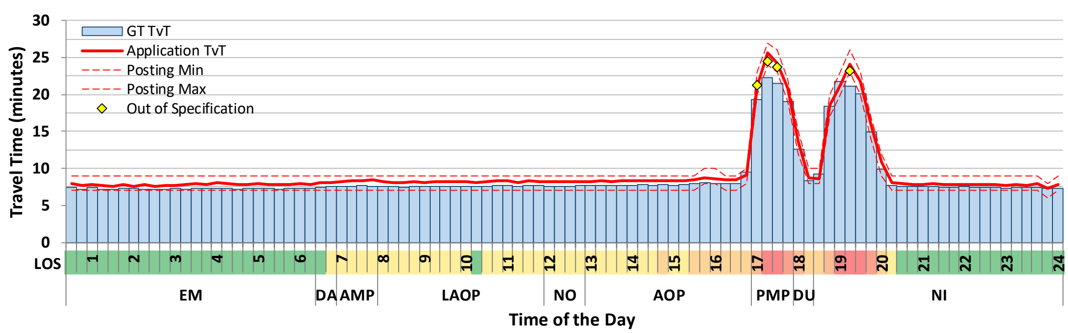
SunGuide Parameters	
timeRangInterval1	2 min
timeRangInterval2	3 min
changeRangeInteral	10 min

Summary: Intervals out of Specification	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
#	0	0	2	1	0	2	4	0	3	12
%	0.0%	0.0%	2.1%	1.0%	0.0%	2.1%	4.2%	0.0%	3.1%	12.5%

Figure 98: Travel Time Application Behavior: Real VDS Errors

Faced with this situation, it would be wise to verify which kind of action would need to be taken to ensure that 95% of the reported intervals are within specification. By changing the error values using the simulation system, it is possible to estimate which detectors would have to be calibrated and which level of accuracy would have to be reached so that the system accuracy test is successful. Figure 99 indicates one possible scenario where the decision maker might have selected the VDS in Link 7 and sent a team to execute a calibration. Considering that the calibration was successful and now the detector error is on average 1.4% for speed and 1.7% for volume, the system would now behave as intended, with only 4 intervals out of specification, or 95.8% compliance.

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	-7.5%	2.4%	-7.5%	-6.3%	-15.2%	-1.8%	-15.2%	-3.0%	-7.5%	2.4%	-7.5%	-6.4%	1.1%	2.5%	-15.3%	-3.0%	-7.5%	2.4%
L2	-4.8%	-0.1%	-4.8%	-0.3%	-8.8%	-2.6%	-8.8%	0.0%	-4.8%	0.0%	-4.7%	-0.1%	1.0%	1.3%	-8.8%	0.1%	-4.8%	0.0%
L3	-6.2%	0.6%	-6.2%	-0.2%	-4.4%	-1.3%	-4.4%	-0.7%	-6.2%	0.7%	-6.3%	-0.1%	2.0%	-1.2%	-4.4%	-0.6%	-6.2%	0.5%



SunGuide Parameters	
timeRangInterval1	2 min
timeRangInterval2	3 min
changeRangeInteral	10 min

Summary: Intervals out of Specification	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
#	0	0	0	0	0	0	3	0	1	4
%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.1%	0.0%	1.0%	4.2%

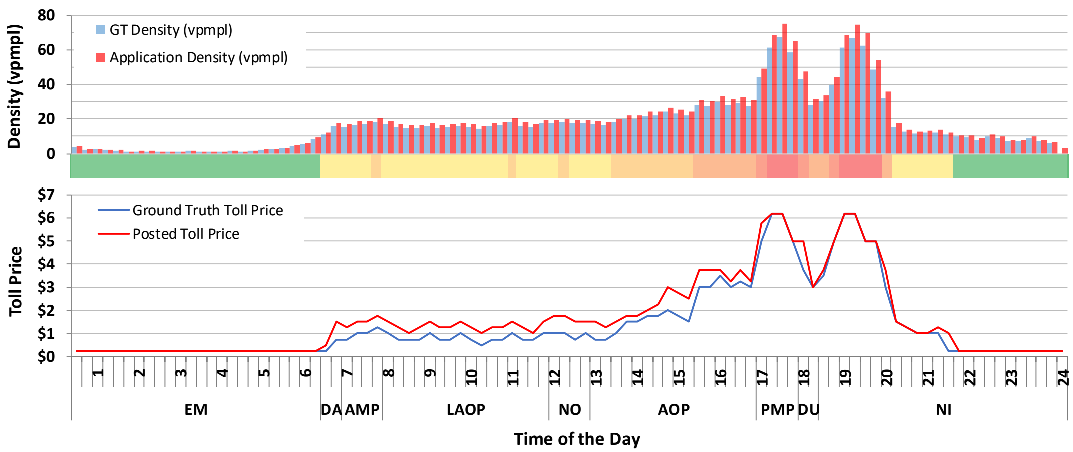
Figure 99: Travel Time Application Behavior: Real VDS Errors after Intervention

5.1 Pricing Strategies in Tolling Application

This section builds on the application performance analysis by presenting the toll pricing application. The view presented in the figures to follow is somewhat similar to the previous ones for travel time applications. The main differences are described in the sequence. The top chart (*y-axis* given as “Density (vpmpl)”) depicts the density information. The blue bar chart presents the density calculated for perfect VDS data. The red bar chart presents the calculations under the simulated accuracy degradation scenario indicated in the top table. The color scale, from green to red, in the bottom of this chart indicates the LOS, given the calculated density for the perfect VDS data.

The second chart (y-axis given as “Toll Price”) depicts the toll prices for each one of the periods. Following the color convention, the blue line series indicates the prices calculated for perfect VDS data and the red line series indicates the posted toll price considering the VDS detection errors. The *x-axis* shows the periods of the day, organized in 15-minute intervals.

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%
L2	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%
L3	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%	-10.0%	-5.0%

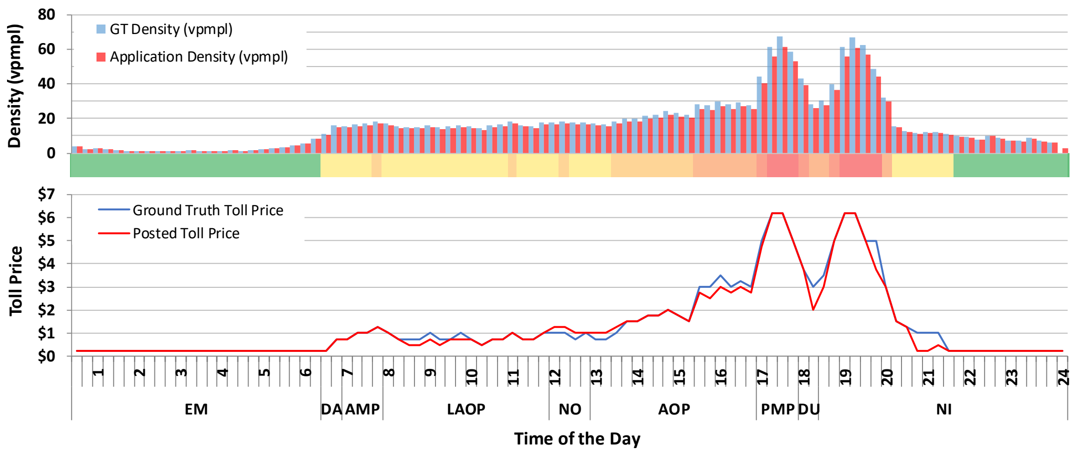


	Summary: Intervals out of Specification									
	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
Intervals	0	2	4	16	4	16	1	1	4	48
Percent Intervals	0.0%	2.1%	4.2%	16.7%	4.2%	16.7%	1.0%	1.0%	4.2%	50.0%

Figure 100: Toll Pricing Application Output (Error of -10% in Speed and -5% in Volume)

Figure 100 and Figure 101 show how the application would be affected by the extreme situation where all detectors have accuracy exactly at the limits stablished in the Specification 660 (*9*). Once again, this analysis demonstrates that the application could potentially suffer loss in performance. For simulated speed errors of 10% in all VDS (Figure 100), 50% of the 96 15-minute intervals would be posting incorrect toll prices. This situation would result in posting prices systematic higher than the correct value. On the other hand, speed increases of 10% (Figure 101) would generate the under estimation of toll prices.

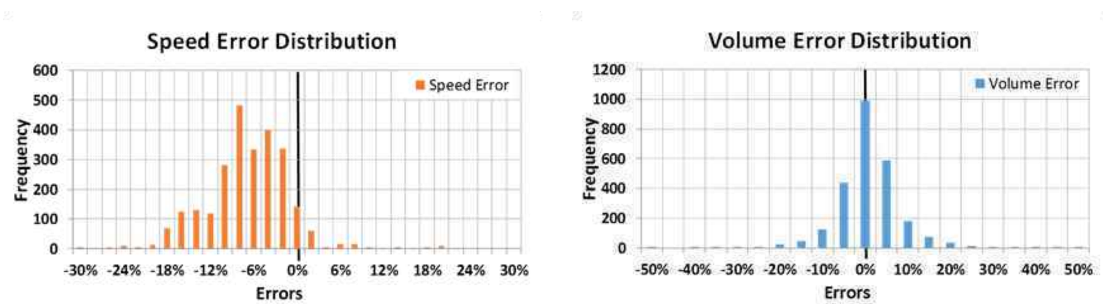
	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%
L2	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%
L3	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%	10.0%	-5.0%



	Summary: Intervals out of Specification									
	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
Intervals	0	0	0	5	3	9	1	1	5	24
Percent Intervals	0.0%	0.0%	0.0%	5.2%	3.1%	9.4%	1.0%	1.0%	5.2%	25.0%

Figure 101: Toll Pricing Application Output (Error of 10% in Speed and -5% in Volume)

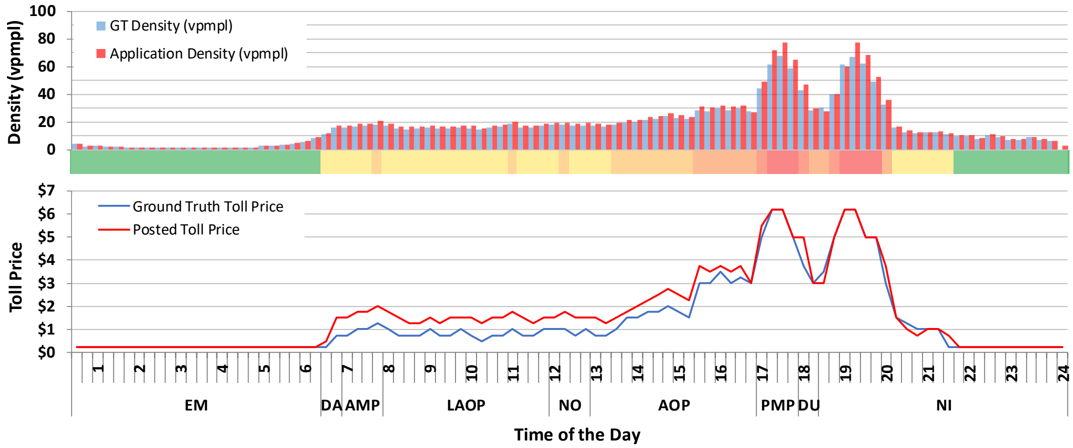
The speed error profile for next three scenarios maintains the same consistency, variating accuracy from skewed left (Figure 102 and Figure 103), to skewed right (Figure 104 and Figure 105), and including accurate, centered on 0% error (Figure 106 and Figure 107). It is noticeable that the system output deteriorates significantly more for underestimations of speed. Nevertheless, this conclusion cannot be generalized and it is only applicable to this particular segment configuration, given this traffic pattern. One of the reasons that add difficulty to the generalization of the concepts is the nature of the decisions, including the concept of ranges for price changing and minimum and maximum allowed toll prices. This type of analysis, considering the extreme points of the specification, is useful to illustrate the error effects, but it is a scenario very unlikely to happen. For each one of the following three scenarios, we first present the error distributions for speed and volume, followed by the resulting effect in the application output.



(a) (b)

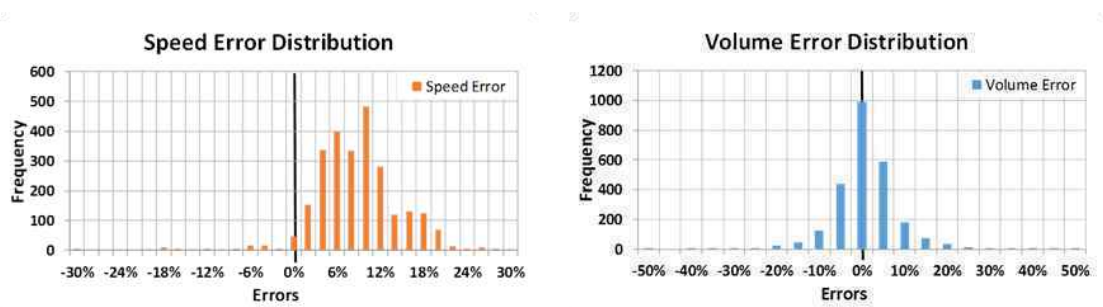
Figure 102: Speed and Volume Error Distribution: Speed Underestimation

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	-7.5%	2.4%	-7.5%	-6.3%	-15.2%	-1.8%	-15.2%	-3.0%	-7.5%	2.4%	-7.5%	-6.4%	-15.4%	-1.7%	-15.3%	-3.0%	-7.5%	2.4%
L2	-4.8%	-0.1%	-4.8%	-0.3%	-8.8%	-2.6%	-8.8%	0.0%	-4.8%	0.0%	-4.7%	-0.1%	-8.9%	-2.7%	-8.8%	0.1%	-4.8%	0.0%
L3	-6.2%	0.6%	-6.2%	-0.2%	-4.4%	-1.3%	-4.4%	-0.7%	-6.2%	0.7%	-6.3%	-0.1%	-4.4%	-1.2%	-4.4%	-0.6%	-6.2%	0.5%



	Summary: Intervals out of Specification									
	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
Intervals	0	2	4	16	4	15	1	1	5	48
Percent Intervals	0.0%	2.1%	4.2%	16.7%	4.2%	15.6%	1.0%	1.0%	5.2%	50.0%

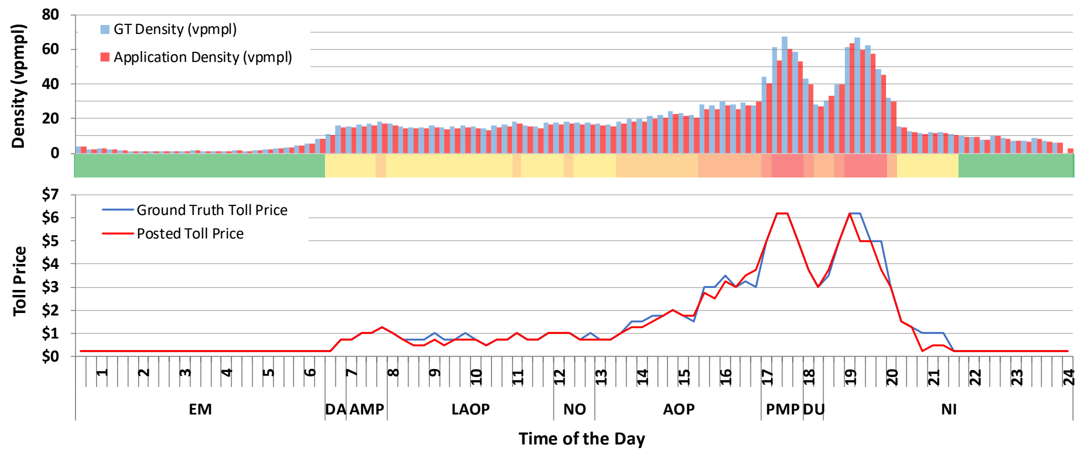
Figure 103: Toll Pricing Application Output (Speed Underestimation)



(a) **(b)**

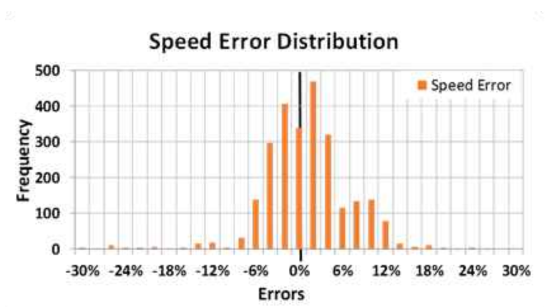
Figure 104: Speed and Volume Error Distribution: Speed Overestimation

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	7.5%	2.4%	7.5%	-6.3%	15.2%	-1.8%	15.2%	-3.0%	7.5%	2.4%	7.5%	-6.4%	15.4%	-1.7%	15.3%	-3.0%	7.5%	2.4%
L2	4.8%	-0.1%	4.8%	-0.3%	8.8%	-2.6%	8.8%	0.0%	4.8%	0.0%	4.7%	-0.1%	8.9%	-2.7%	8.8%	0.1%	4.8%	0.0%
L3	6.2%	0.6%	6.2%	-0.2%	4.4%	-1.3%	4.4%	-0.7%	6.2%	0.7%	6.3%	-0.1%	4.4%	-1.2%	4.4%	-0.6%	6.2%	0.5%

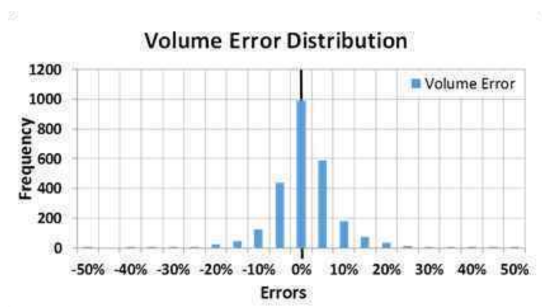


	Summary: Intervals out of Specification									
	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
Intervals	0	0	0	5	1	9	0	0	6	21
Percent Intervals	0.0%	0.0%	0.0%	5.2%	1.0%	9.4%	0.0%	0.0%	6.3%	21.9%

Figure 105: Toll Pricing Application Output (Speed Overestimation)



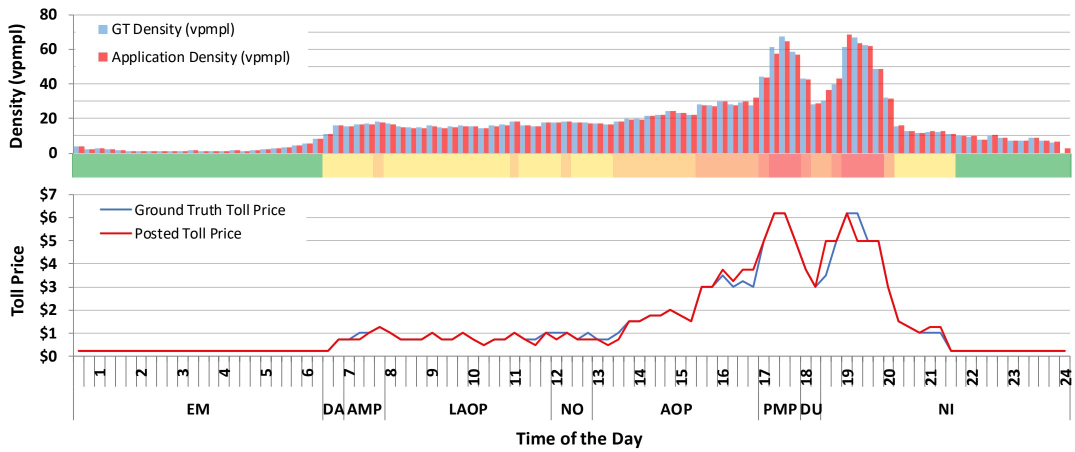
(a)



(b)

Figure 106: Speed and Volume Error Distribution: Accurate Speed

	Link 1		Link 2		Link 3		Link 4		Link 5		Link 6		Link 7		Link 8		Link 9	
	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume	Speed	Volume
L1	-0.2%	2.4%	-0.2%	-6.3%	7.6%	-1.8%	7.6%	-3.0%	-0.1%	2.4%	-0.1%	-6.4%	7.7%	-1.7%	7.7%	-3.0%	-0.2%	2.4%
L2	-2.9%	-0.1%	-2.9%	-0.3%	1.2%	-2.6%	1.2%	0.0%	-2.8%	0.0%	-3.0%	-0.1%	1.2%	-2.7%	1.1%	0.1%	-2.8%	0.0%
L3	-1.4%	0.6%	-1.4%	-0.2%	-3.3%	-1.3%	-3.3%	-0.7%	-1.4%	0.7%	-1.4%	-0.1%	-3.2%	-1.2%	-3.3%	-0.6%	-1.4%	0.5%



	Summary: Intervals out of Specification									
	EM	DA	AMP	LAOP	NO	AOP	PMP	DU	NI	TOTAL
Intervals	0	0	1	1	2	6	0	0	4	14
Percent Intervals	0.0%	0.0%	1.0%	1.0%	2.1%	6.3%	0.0%	0.0%	4.2%	14.6%

Figure 107: Toll Pricing Application Output (Accurate Speed)

The data used to simulate the VDS errors are based on the analyses and findings in Chapter 4. As expected, the best performance happened in the third scenario, where the simulated errors, both for speed and volume, are accurate (centered on zero). Even though the VDS consistency isn't changed, it is demonstrated that, by increasing the accuracy the system's performance increases significantly. As discussed in Section 0, the approach suggested here allows the verification, through simulation, of the relevant actions that should be prioritized to ensure that a desired application performance is maintained.

5.2 Application-Driven Requirements

The previous analysis shows that relying on individual VDS acceptance tests may not be enough to guarantee good quality in the system outputs. In addition to defining VDS unity testing, the system could benefit from requirements that specify minimum performance levels that would, from the application perspective, guarantee a certain output quality. Consider the toll pricing application as an example. Relying on the data provided by a series of detectors from a segment (nine for the segment considered in this study), one could consider a requirement in the form: "The value charged for the toll shall meet the true value of the toll price for at least 95% of the daily intervals, given a ±$0.25 error tolerance". In this situation, testing individual VDS to make sure the current requirements are met (95% accuracy for volume and 90% accuracy for speed) may not suffice to guarantee the outcome of the application is within the required ranges.

Before presenting our suggested approach, let's add one more layer of complexity to better demonstrate the relevance of our suggested approach. In the previous two sections (Section 6.2

and Section 5.1) we demonstrated that the current VDS accuracy performance levels not necessarily ensure that the outcomes of the applications would be correct. Previously we did that considering the applications individually. Now we take into consideration a segment of road that has a network of VDSs, whose data are used for multiple applications. Consider that, the same segment previously described and analyzed, has now two applications operating based on the data from the segment. Simply testing each VDS as individual units given the state of practice doesn't guarantee proper output for the applications.

Nevertheless, the tests in the field have to be performed on individual detectors. What our approach suggests is that the required accuracy for each VDS must consider the application needs. If we consider the following requirements, we would be able to define minimum levels of accuracy that must be maintained by each VDS:

- Travel Time Application: "When posting travel times, the system shall post intervals that contain the true travel time for at least 95% of the daily intervals".
- Toll Pricing: "The value charged for the toll shall be the same as the true toll price for at least 95% of the daily intervals, given a ±$0.25 error tolerance".

It is evident that additional requirements would have to be present to define some specific aspects. As an example, consider for both requirements, the need for the true value of travel time and also toll price. In our study, we obtain the true values from the simulation model and calculate the ground truth according to the needs of each application. Figure 108 depicts the findings of the study considering both applications.

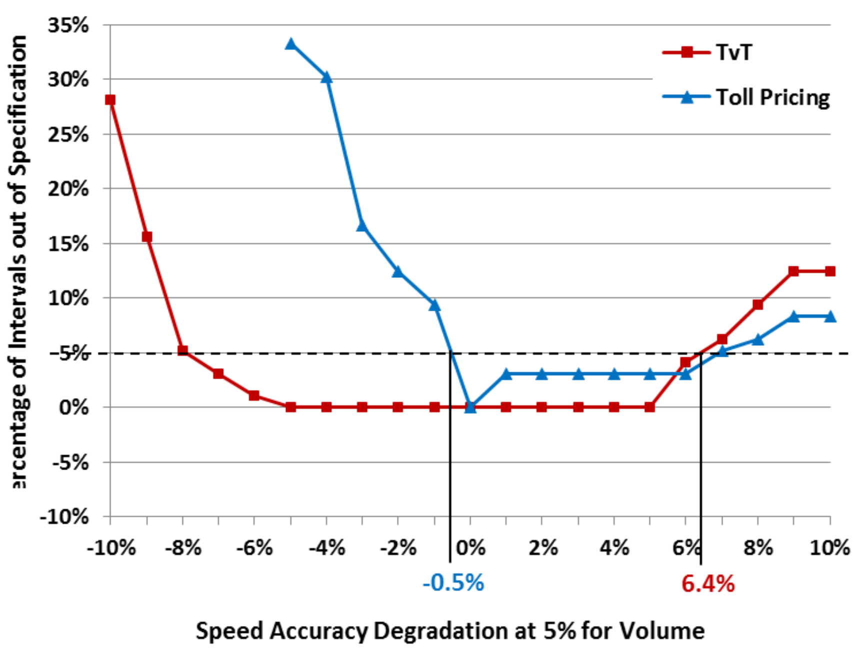


Figure 108: Application-Driven Minimum Accuracy Level

In Figure 108, the *y-axis* shows the percentage of intervals out of specification in a given day. The *x-axis* shows the speed accuracy degradation. As we can see, the lower limit is defined by the toll pricing Application. The travel time application would have at least 95% of the intervals reporting the true value for speed accuracy degradations in the order of -8%. The toll pricing application requires the VDS accuracy degradation to be no less than -0.5%. The upper limit on the other hand is defined by the travel time application, set at a maximum 6.4% speed accuracy degradation. It is also noticeable that the upper level requirements of both applications is very close, while in the lower level the travel time application has more room for error.

Using the travel time and toll pricing simulation framework we demonstrated the process of deriving unit testing accuracy requirements from application accuracy needs. In segments with multiple applications, the most restrictive accuracy levels shall

7 Main Maintenance and Calibration Practices

ITS deployments are primarily executed via design-build projects. The selected firm is allowed to use any device/materials from the Approved Product List (APL). In the case of MVDS, this includes devices that have passed all requirements and testing specified in FDOT standard specification 660. For that reason, no further testing is required other than integration/installation tests. Once in operation, maintenance is outsourced to contractors based on a master agreement. Maintenance tickets are triggered from the traffic management centers due to a number of reasons such as but not limited to:

- No communication
- No data
- Failure to trigger slow-speed alarm
- False congestion alarms
- System reports

When these events happen, the TMC performs remote troubleshooting before issuing a maintenance ticket. These tickets enter a job queue and are prioritized based on the MVDS usage (e.g., express lanes or performance monitoring are priority over other applications).

In most districts, preventive maintenance is limited to a fixed number of site visits per year. In addition to preventive maintenance, additional maintenance activities are charged as a fixed cost per visit per site. Maintenance costs vary by region based on distance and detector density among other operational factors. These maintenance activities and agreements usually involve the following:

Table 28: Maintenance Activities for MVDS

Maintenance Activity	Overview
Minor repairs	Involve troubleshoot, reset, reboot, and basic diagnostics
Preventive maintenance	Inspect, test, and calibrate if necessary
Device Replacement	Troubleshoot, remove, install, integrate, and test new device

1.2 Sample Size and Inspections

MVDS accuracy presents inherent variation that can be the result of different effects (environment, technology, hardware, software, etc.). Accuracy may tend to converge to the target value for sufficiently large number of observations. However, in practice, the most used aggregation interval is 15 minutes. Roadway capacity serves as the natural limit on the maximum number of vehicles that can be observed on the road at any given time. For example, observed traffic conditions at one of the data collection sites gave 1,400 vehicles per lane as the maximum observed volume during peak hours. Data on MVDS performance under several conditions suggest that MVDS may present increased variability for speed under congested conditions (LOS E, F). Therefore, it is not recommended to perform inspection or installation tests during congested conditions. Even though more observations are collected, the nature of the technology may induce additional errors. Notice that the recommendation on this report is for additional performance tests on congested conditions. The main reason is to avoid troubleshooting an operational MVDS due to natural and unavoidable variation due to its technology. However, for certification, the congested situation is key to decide over a particular technology or brand. Since most of the TMCs apply a form of active congestion management. Therefore, accuracy on congested traffic conditions can serve as a decision criterion.

The conditions to obtain a good estimate of accuracy, especially for speed are conditions with LOS B, C, and D. These measurements can be taken from the TMC and can be used for quality control purposes. The objective is to have as many samples as possible to ensure informed decision making with respect to maintenance. When using small tests such as in the case of a crew in the field, it is possible to find apparent non-compliant samples when in reality this could be part of the natural variation.

To better illustrate the idea a theoretical simulation of the volume counting behavior was performed. The simulation assumed that the MVDS has accurate true-zero measurements and only when a vehicle is present there is a probability that the vehicle is not sensed correctly. In those cases, the vehicle may be overcounted or undercounted with equal probability. Several numerical simulations were run (1,000 replicates) for each level of observed volume (N). Several accuracies ranging from 0.8 to 0.98 were tested. The assumed failure mechanism is presented in Figure 109.

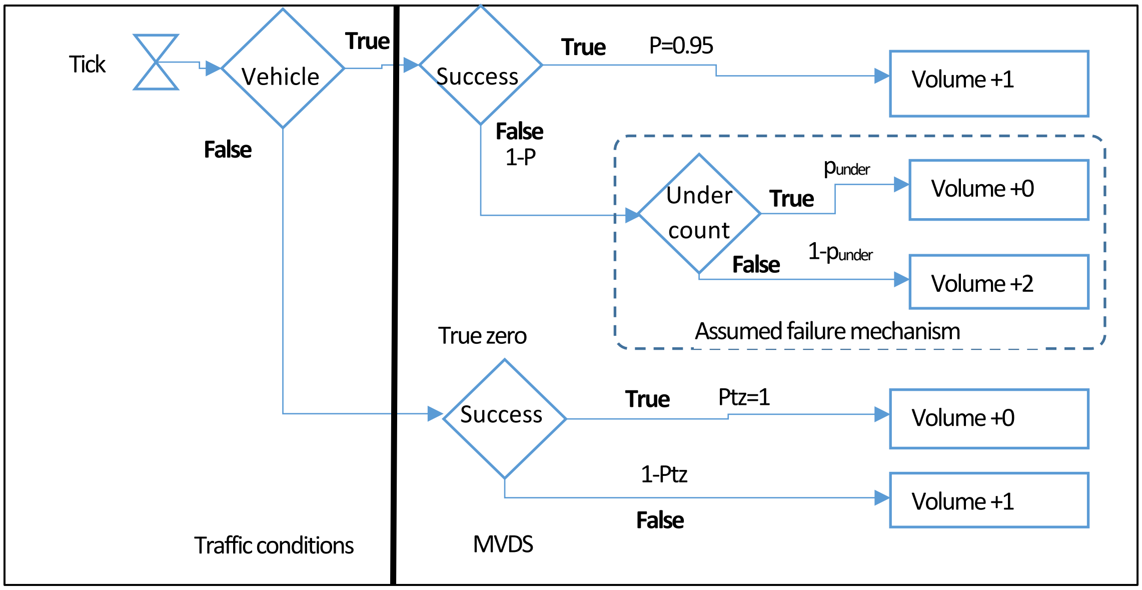


Figure 109: Assumed Failure Mechanism for Counting

Based on the assumed failure mechanism all the cases converge to the average value of zero, however the variability differs and the number of replications (points) outside the required accuracy values serves as an indication of the consistency of the MVDS. Even though the global average tends to agree, the decisions on TMC operations are taken with the result of a single point (15 min aggregation) as it is observed in Figure 110 this point may misrepresent the traffic conditions due to increased variability. For inspection and maintenance, the implication of natural variation is taking a sample of a MVDS that is operating correctly and conclude that recalibration is needed.

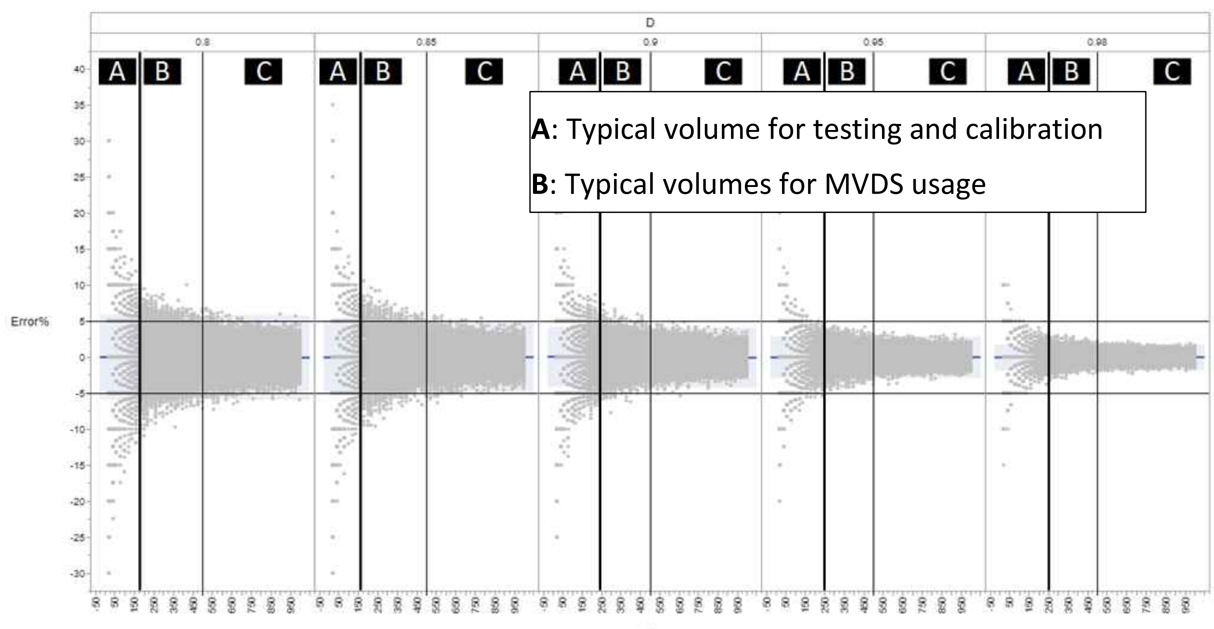


Figure 110: Volume Measurement Failure Mechanism Simulation

For inspection purposes, if an MVDS has a theoretical accuracy of 95% with perfect zero and symmetric failure mode a sample size in excess of 160 is recommended. The effect of a smaller sample size is increasing false positive test results. For MVDS installation tests this is equivalent to assume the MVDS is out of specification when in reality is operational. For a sample size of 20 the probability of false positive is 50%. As the volume increases, the chances of a false positive error (type I) decrease (see Figure 111)

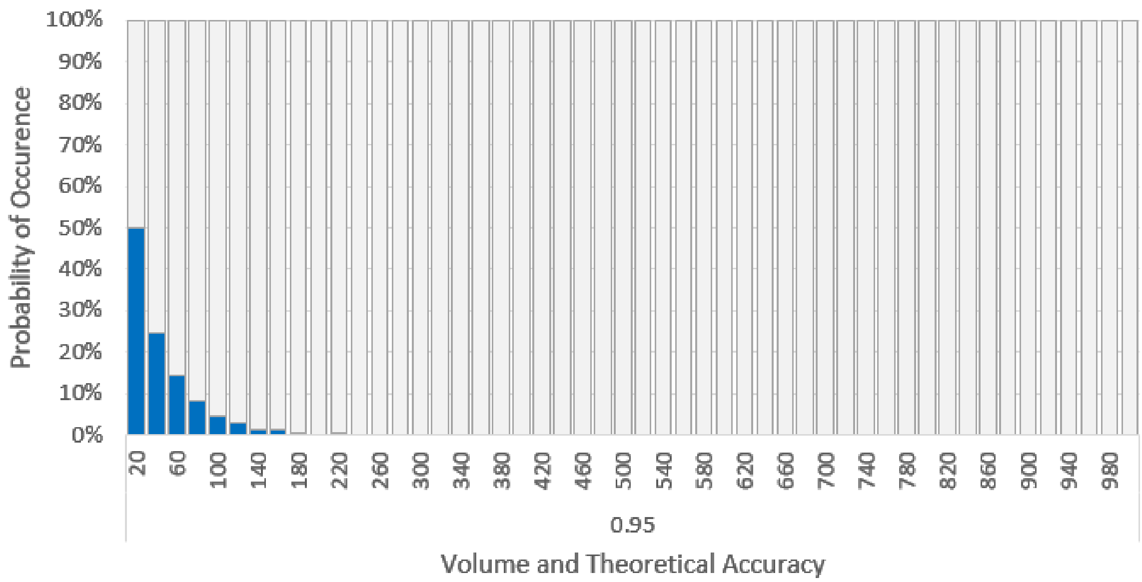


Figure 111: Suggested Sample Size for Volume Accuracy Inspections

For level of service A, it is important to note that there could be variability associated with small volumes. In addition, there is the possibility for the device not having a true zero measurement (counting a vehicle when there is none).

1.2.1 Inspections

Figure 112 presents any day taken at random in one of the D7 testbed sites. (MP 30.0 SB). The y axis represents the signed accuracy rating. The lower specification limit and the upper specification and the zero line are plotted. The plot is divided by MVDS type. The top row corresponds to ISS-G4, the middle row to W-HD and the last row to a W-SS105. The x-axis represents time of day with the TERL certification tests time intervals marked. The plot is color coded by lane density expressed as level or service (LOS).

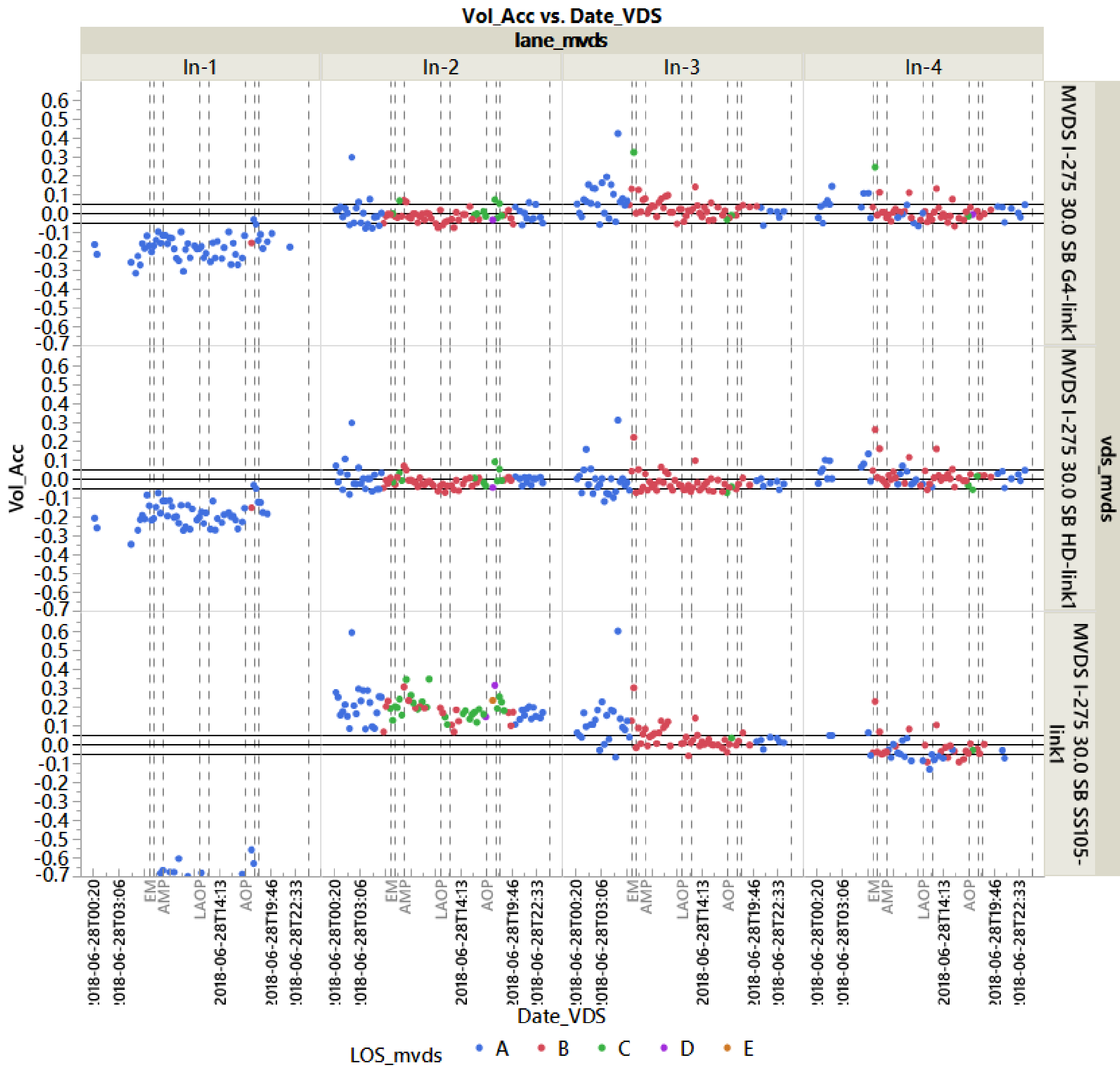


Figure 112: Volume at MP 30.0 I-275 SB by Time of Day, MVDS, and Lane, Color Coded by LOS

In this chart each point represents a 15-minute interval which is the inspection unit. For lane 1 (closest to the detector) it is observed that there are some calibration issues. The sign of the deviation indicates that the MVDS is undercounting vehicles. For the case of the W-SS105 the volume error for lane 1 is severe. This is a problem of accuracy or bias and can be resolved by calibrating the sensor until centered about 0.

Both G-4 and W-HD present a similar behavior for the remaining lanes. The accuracy is acceptable with minimum bias. The consistency of the device is related to the variability of the error. Together with the accuracy, the consistency may determine how many individual intervals will fall outside the specification limits. Any MVDS may have an acceptable average accuracy but the consistency may be such that it may present a considerable amount of intervals outside the specification limits. The implication of this for TMC operations is that some decisions on metering rates, toll pricing etc., are being made based on an incorrect assessment of the traffic conditions. TMC applications are often associated with a form of active traffic management therefore it is important to guarantee that the supporting traffic sensor subsystem will provide the required levels of accuracy. The standard specification test can be updated to accommodate this situation by collecting several samples of the inspection unit (15-minute interval) at the time of day typically associated with increased traffic conditions.

The fraction of non-conforming intervals for speed and volume can be specified so that the TMC to increase the quality of the information being used in the TMC decision making process. This can be expressed as “The VDS shall provide a <Volume> accuracy within <5%> of the reference value for a 15-minute interval for 95% of the times during LOS C, D, E, and F”. A more technical statement could be “The probability that a 15-minute interval volume accuracy is within 5% of the ground truth value under traffic conditions C, D, E, and F shall be 95%”. The advantage of the proposed requirement is that it allows the certification process to focus on the features that are needed for the current TMC applications without drastically changing the current calculations.

A similar analysis for speed is presented in Figure 114. At the same location, the effect of the setup is such that speed is overestimated by the G4 and W-HD MVDS’s. For the remaining lanes the G4 went from centered to under estimating speed measurement with distance from the pole. The W-HD also present the same trend with more measurements below the center line zero as it goes away from the pole. For both G4 and W-HD, the variation occurs within the specification limits. However, the W-HD presents a more consistent behavior. The W-SS105 presents systematic trend from lane 1-4 which can be resolved with calibration. The detector appears to have the consistency required to meet the specifications

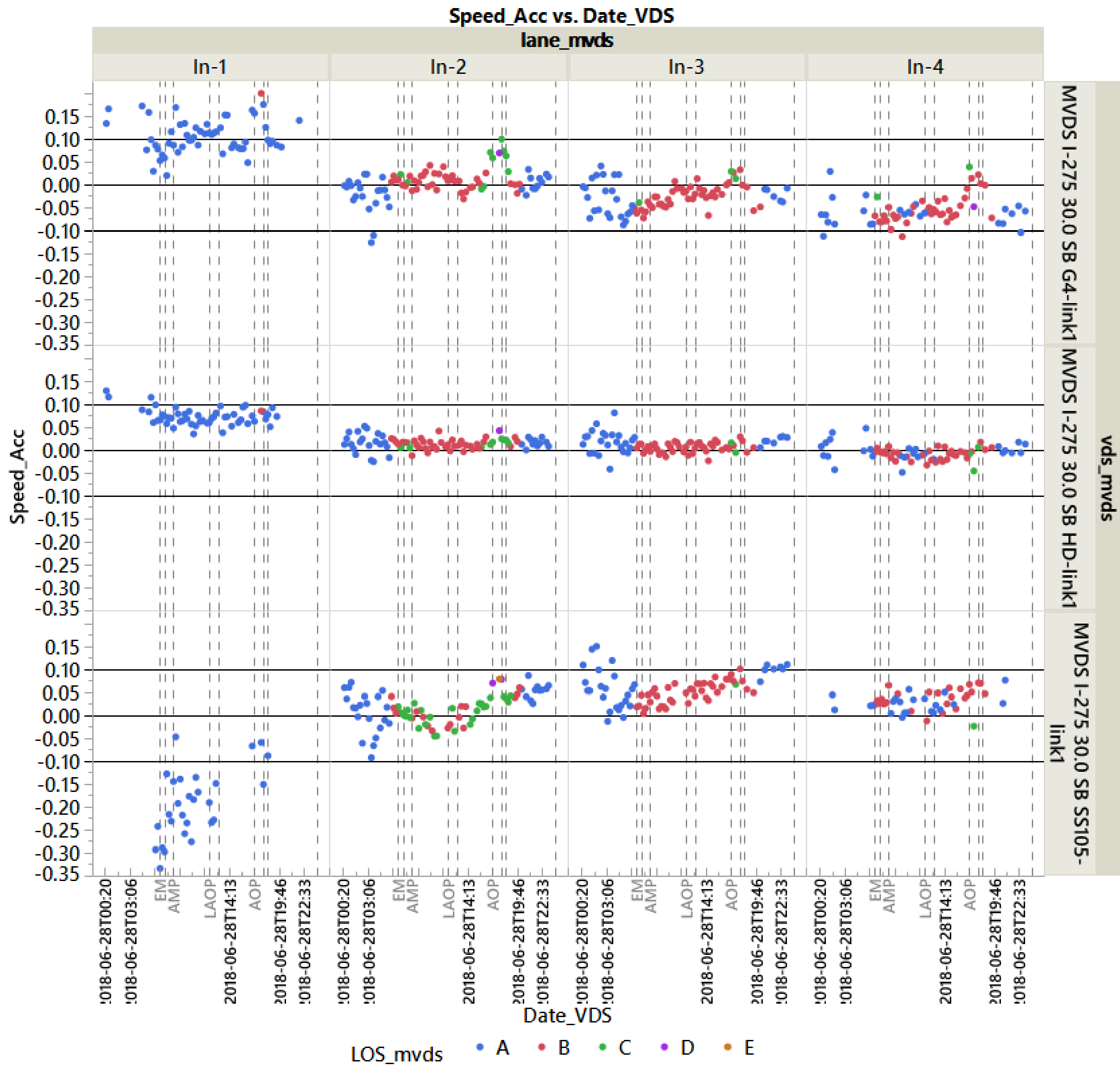


Figure 113: Volume at MP 30.0 I-275 SB by Time of Day, MVDS, and Lane, Color Coded by LOS

1.3 MVDS States and Maintenance Costs

Based on an analysis of the state of the practice, an MVDS can be represented by three main logical components: communication, detection, and data quality. Communication and detection are related to physical elements. Configuration is related to MVDS hardware/software settings that will directly affect the data quality. Any of these components can be represented by a series of states and transitions as represented in Figure 114. An operational MVDS can go to a degraded state through a configuration drift. This means the device may lose all initial configuration settings. A degraded MVDS may have signal and report data, however some of the data may not be suitable for use due to degradation. The TMC may send the maintenance crew to check the status of the device and confirm whether the device has failed or not. A sudden failure of either the communication equipment or the detection equipment can bring a MVDS to a failed state directly. Once the MVDS is in the failed state, the TMC issues a maintenance ticket. The maintenance contractor repairs the MVDS and notifies the TMC. The MVDS is repaired and operational; however, this has not been confirmed by the TMC. Once the TMC confirms that the MVDS is enabled and operating as intended, the status becomes operational.

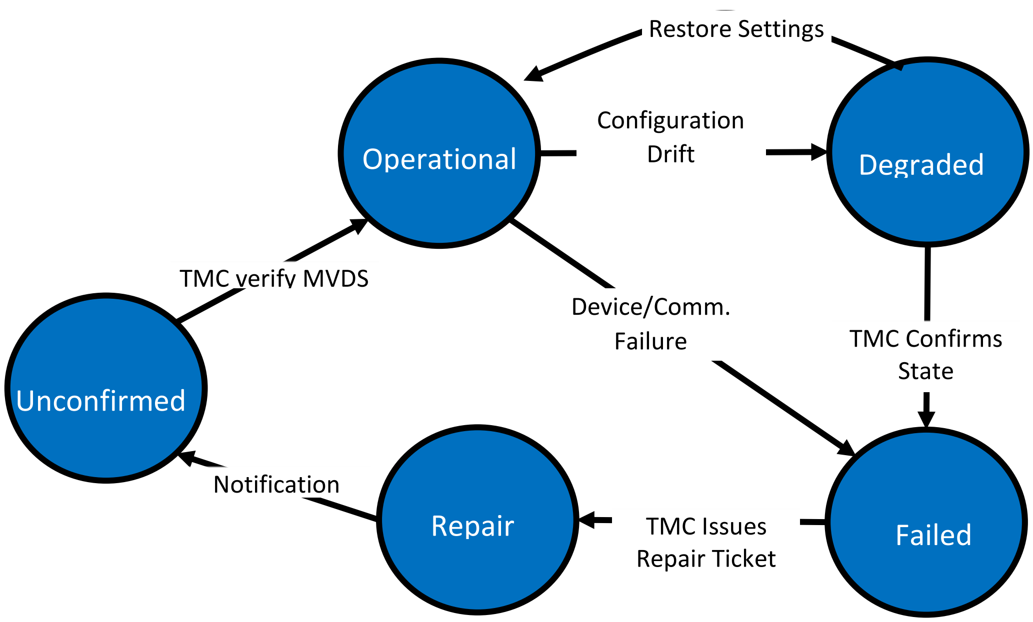


Figure 114: States and Actions for MVDS (Device, Communication, and Data Quality)

Cost reductions can be achieved by designing and deploying technology with MVDS site accessibility. Remote troubleshooting can be performed at the TMC before incurring in additional costs of sending filed maintenance crew for routine procedures. In addition, the field maintenance crew time can be allocated more efficiently if some basic diagnosis results are known in advance.

Table 29: Suggested Maintenance Action on the TMC

Action	Capability
Reset devices	Include provisions to provide remote rebooting capability for the MVDS and other components (including switch)
Clear ARP table	Perform command remotely
Download MVDS configuration	Save point for known working configurations. Deploy last known working configuration remotely
Evaluate accuracy performance	Remotely count and estimate speed
Test or confirm data quality	Have a backup tool to evaluate accuracy tests
UPS resent and check	Remotely monitor, and reset UPS

A MVDS is considered non-operational state when either detection, communication or data quality are not operating as intended. When physical failure occurs, the device is not responsive and there are a limited options for a TMC operator. However, in situations when communication to the MVDS site is operational, the TMC operator can perform initial troubleshooting by remotely resetting the devices and deploying known configurations.

1.4 Volume and Speed Samples

In order to facilitate a remote assessment or confirmation, a spreadsheet-based video tool is proposed. The tool works in MS Excel and makes use of Windows media player control. The TMC operator can record 15 minutes of traffic using any open source video recorder (e.g., VLC). The tool works best with Audio Video Interleave (*.avi) extension but any video format compatible with windows media player can work (e.g., wmv, wma, wm, asf, avi, mpg, mpeg, mp4, m4v,.3g2,.3gp2,.3gp, and 3gpp)

The tool allows video to run frame-by-frame using key strokes. Also, volume counts can be performed via key strokes by mapping lanes to keys on the keyboards (e.g., a for left lane). It also allows synchronization of video segment start time with any custom timestamp. This will enable the user to keep track of time in the same units of the video or MVDS report. Time is counted using the video framerate.

The tool also has the capability of overlaying reference lines or traps for speed estimation. This feature is useful for a fixed camera and requires some preprocessing to calibrate the tool. Once calibrated it may be useful to estimate speed.

The tool provides support for data analysis and for standard 660 certification test data analysis. Finally, since the tool was developed in excel it can be extended by the user to produce any reports or analysis as required. The tool can be used by TMC operators and maintenance crew to perform acceptance tests and to double check inspection or calibration procedures.

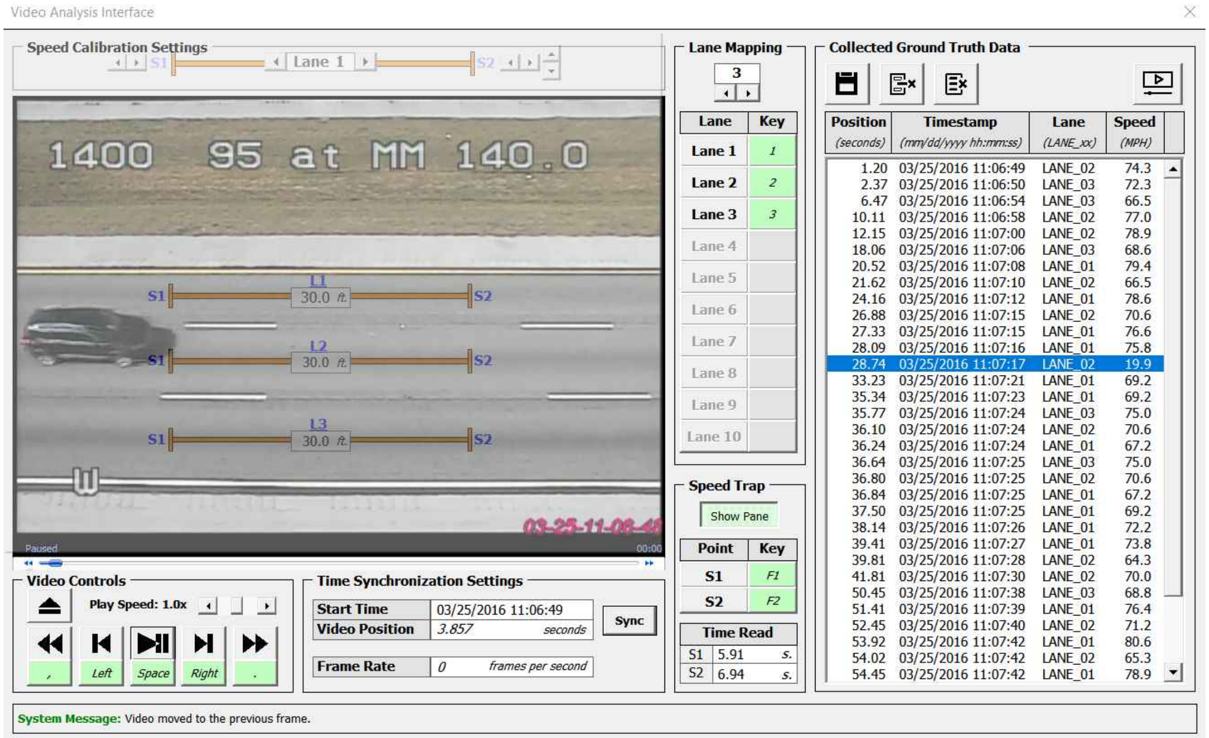


Figure 115: Screenshot of Proposed Spreadsheet-Based Video Tool to Take Volume and Speed Measurement from a Video Segment

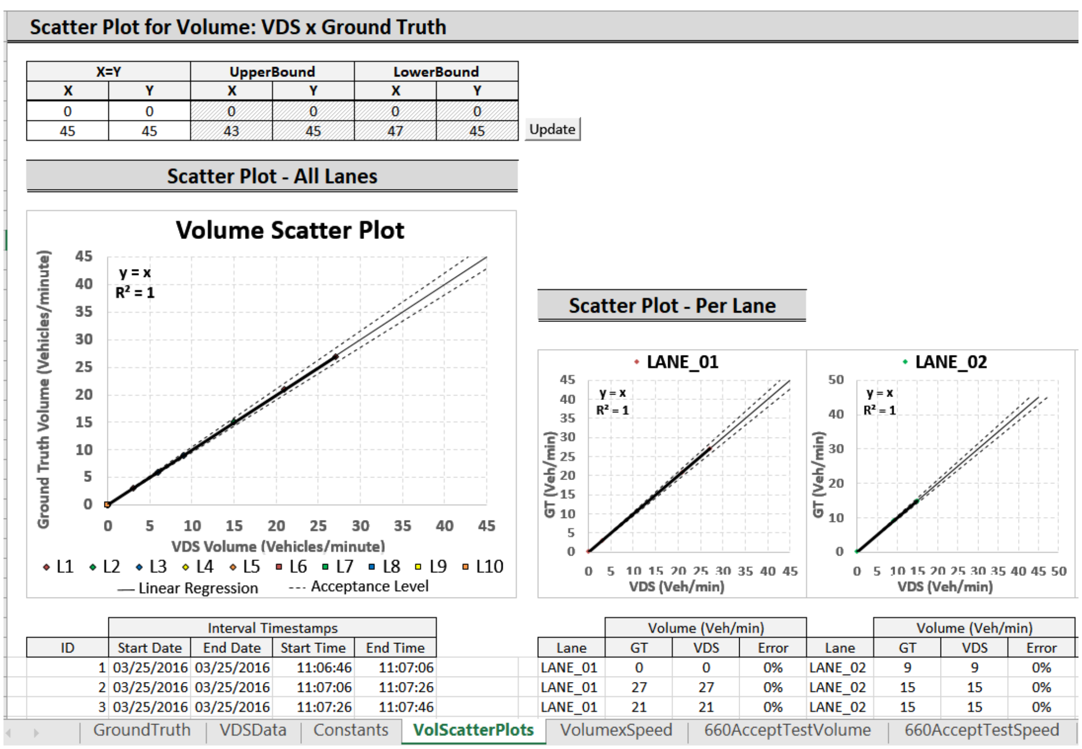


Figure 116: Screenshot of the Data Analysis Tab of the Proposed Tool

8 Conclusions and Recommendations

This project analyzed the vehicle detection systems from a data quality and system engineering point of view. Special attention was given to microwave vehicle detection systems (MVDS) since this is the most widely used technology for freeway applications. A combination of site visits, interviews, field data collection and historical data analysis was used to assess the aspects of data quality for MVDS.

Several data collection and data sources were analyzed. MVDS are mainly provided by two manufactures Wavetronix and ISS with different models. Data provided form District 1, District2 was analyzed. Data was also collected via video from the TMC in District 4. District seven set up a testbed in 2014 in the southbound direction in the Interstate I-275. The testbed included different make and models of MVDS co-located with loop detectors. The objective of the testbed is to analyze the accuracy of MVDS over time. The conclusions obtained with the available information are presented below.

8.1 Conclusions

- Accuracy requirements in the U.S varies by state. It was found that in some cases the minimum requirements varied by weather conditions, by lane of traffic or by prevailing speed. The lower bounds on minimum accuracy standards for speed and occupancy were 80 percent of the ground truth. For volume this value was 90 percent. For presence detection (stop bar) the lower bound for accuracy was 95%.
- In some states, the requirement is tied to a specific base interval. For intervals, less than a minute the accuracy requirement may be slightly relaxed (e.g., 90%). For intervals of five minutes or more, a higher level of accuracy is required (e.g., 95%).
- Lack of data quality in detection system is mostly due to installation, configuration or software errors. For instance in District 4 there are no reported incidents on the quality of the MVDS's in use.
- There was no evidence that data quality degradation occur over time with respect to a reference loop detector once a MVDS is calibrated. This was verified in three sites with data analyzed over several years.
- When comparing MVDS data with data from external systems, it is important to pay attention to synchronization issues to avoid overstating accuracy errors.
- Current detection equipment is capable of meeting the standards for speed and volume traffic conditions B, C, and D.
- Speed consistency (variability) is affected for all MVDS technologies for congested scenarios (LOS E, F). However still remains within the target average accuracy.
- Active management applications using traffic density are negatively affected when speed and volume accuracy fluctuate in opposite directions (e.g., speed overestimation and volume underestimation).

- The main reported causes of VDS failures are summarized in Table 30

Table 30: Summary of Causes of VDS Failure

Category	Possible Root Cause	Reported Symptom	Effect
Methods **Hardware** **Environment**	▪ Attachment method ▪ Weak mounting bracket ▪ Birds landing on VDS ▪ Vibrations	▪ Improper tilt angle	Accuracy/Consistency on far-side lanes
Hardware	▪ VDS Aging	▪ Water intrusion ▪ Antenna degradation ▪ Overall physical degradation	Reliability
Hardware	▪ Loss of configuration settings	▪ Traffic data discrepancies in calibration tests	Accuracy/Consistency
Software	▪ Clock synchronization ▪ Improper lane mapping	▪ Traffic data discrepancies in calibration tests	Accuracy/Consistency
Communication	▪ Communication terminal reliability	▪ Communication failures	Reliability
Environment	▪ Detector placement ▪ Truck Traffic ▪ Work zones ▪ Median objects ▪ Temperature	▪ Traffic data discrepancies in calibration tests	Accuracy/Consistency
Environment	▪ Traffic patterns (low density high density)	▪ Traffic data discrepancies in calibration tests	Accuracy/Consistency
Environment	▪ Lightning	▪ Detector off-line	Reliability

8.2 Recommendations

- Implement an automated VDS time synchronization command periodically. The proposed frequency is once per day. This can occur at low traffic periods such as early in the day.
- Synchronization can be triggered from the TMC as a scheduled process via SunGuide or it can be implemented as an automated feature on the MVDS. If implemented in the MVDS,

the agency shall provide a time server in its network. The MVDS shall provide the functionality to update its time at the designated schedule.

- Revise travel time segments periodically to ensure that calculation parameters are properly encoded.
- Revise lane mappings systematically for new MVDS installations. Check for lane mapping errors and correct them.
- Establish inspection counts with more than 60 vehicles per sample for suspect degraded detectors. Verify that the accuracy of the samples does not present any trend. Trends include consistently overcounting or undercounting even if the accuracy is within specifications.
- Designate a position at the TMC to detection issues. This person needs to be trained in MVDSs calibration and troubleshooting.
- Conduct MVDS workshops with SunGuide database administrators, TMC operators, and MVDSs maintainer in common topics in MVDS accuracy such as: data collection, calibration, verification, basic troubleshooting, data management etc. This will help to improve the current practices.
- Integrate SunGuide and MOM systems. Establish a MVDS installation workflow that start with SunGuide and it is pushed to the MOM system. In this way, there is a single source of truth for MVDSs information and all the maintenance data can be exchanged between the two systems.
    - Suggested fields to include in the MOMs MVDS database are: installation date, pole type, mounting height, bracket type, bracket length, pole setback, and tilt angle.
- For installation and inspections it is recommended to use a digital protractor to keep track of tilt angle at installation/calibration.
- For managed lanes application, conduct the calibration tests after all the roadway objects have been installed (e.g., delineators). This will ensure that the calibration procedure will be robust against median objects.
- Establish a set of priority detectors critical to system performance monitoring. This set of critical VDS will receive priority for maintenance and constant health and accuracy monitoring. High priority MVDs may include detectors in sections where there is high variability among lane speeds (e.g., exit ramps).
- Establish performance metrics that takes into consideration communication and detection failures separately.
- Establish a TMC procedure for verification and inspection of a MVDS installation. The procedure shall include calculations and acceptance criteria based on capabilities within reach of TMC operators using CCTV monitoring cameras. A spreadsheet tool was develop to assist TMC operators to conduct remote inspections using CCTV cameras.

- Save MVDS configuration in in the central system and refresh the configuration on the field MVDS after certain period (e.g., quarterly). This process can be automated in SunGuide. In addition, testing for this feature as part of the TERL acceptance test is recommended.
- Test for power on/off recovery of MVDS. Based on review of maintenance records review after power outages, some detectors cannot come back to the same settings. The recommended testing is to turn power on/off and check for changes in accuracy or settings.
- Test for water intrusion as part of the TERL approval tests. These tests shall simulate some field extreme conditions such as heavy rain in a hot day. To replicate field conditions, hot air can be blown to the MVDS until the target temperature is obtained and sprayed with water to test the seals and accuracy. This process can be repeated a number of times to verify performance.
- Revise surge protection procedures to ensure that the latest recommended practices are being followed in the field.
- Revise the reliability requirements for communication terminals. This element has the potential to disable the detection data transfer to the TMC and creates a weak link if its reliability is lower than that of the VDS.
- Revise installation procedure for mounting VDS and provide training material to installers. Installation requirements/training has to be flowed down to field installer to ensure proper implementation.
- Design an MVDS package for new ITS deployments that includes requirements for remote reset capabilities for field equipment (e.g., reset detector, switch, UPS, clear ARP tables, etc.). In this way, basic troubleshooting can be shifted to the TMC to avoid mobilizing crews to reset different components.
- Create a reset MVDS routine in SunGuide to automatically attempt to bring an MVDS back to operation. This may include but not limited to turning on/off devices, cleared memory, and deploy last known configuration. If communication, power, and mechanical conditions remain the same, and the device cannot be brought back to calibration status then there may be some aspects to work with the MVDS manufacturer.
- Keep the current standards for speed, volume, and occupancy but apply the standards by traffic conditions, being stricter for AM/PM peak conditions. This will be the decisive criteria to recommend MVDS to be used in active traffic management applications (express lanes, running shoulder, ramp metering).
- Implement a true zero tests for low volume conditions. This test shall be strict for MVDS to be used in presence detection applications (queue detectors, wrong way detection). A confusion matrix is recommended for this traffic conditions (e.g., number of false detections, number of omissions).

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